Strange Quark Matter in Stars: A General Overview

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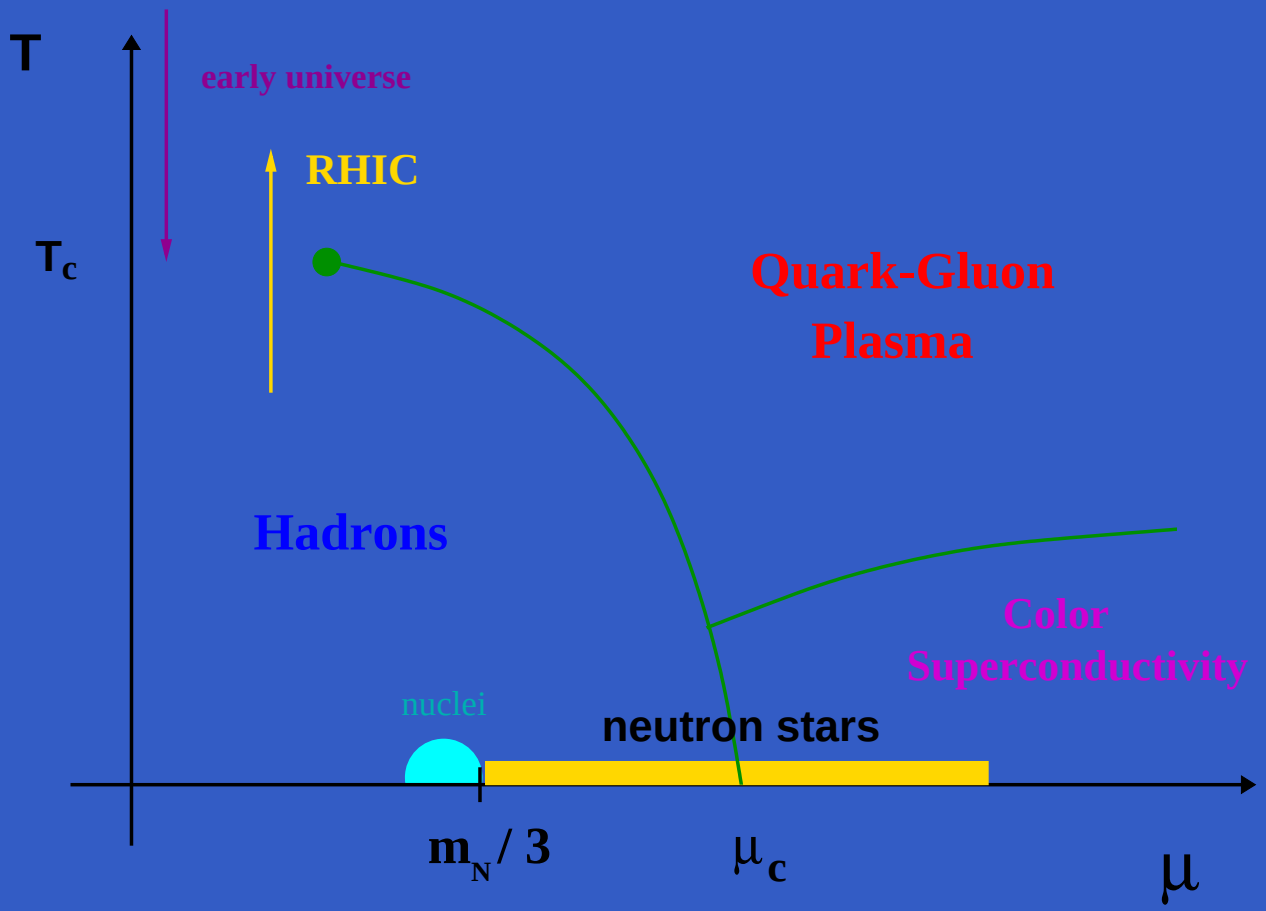
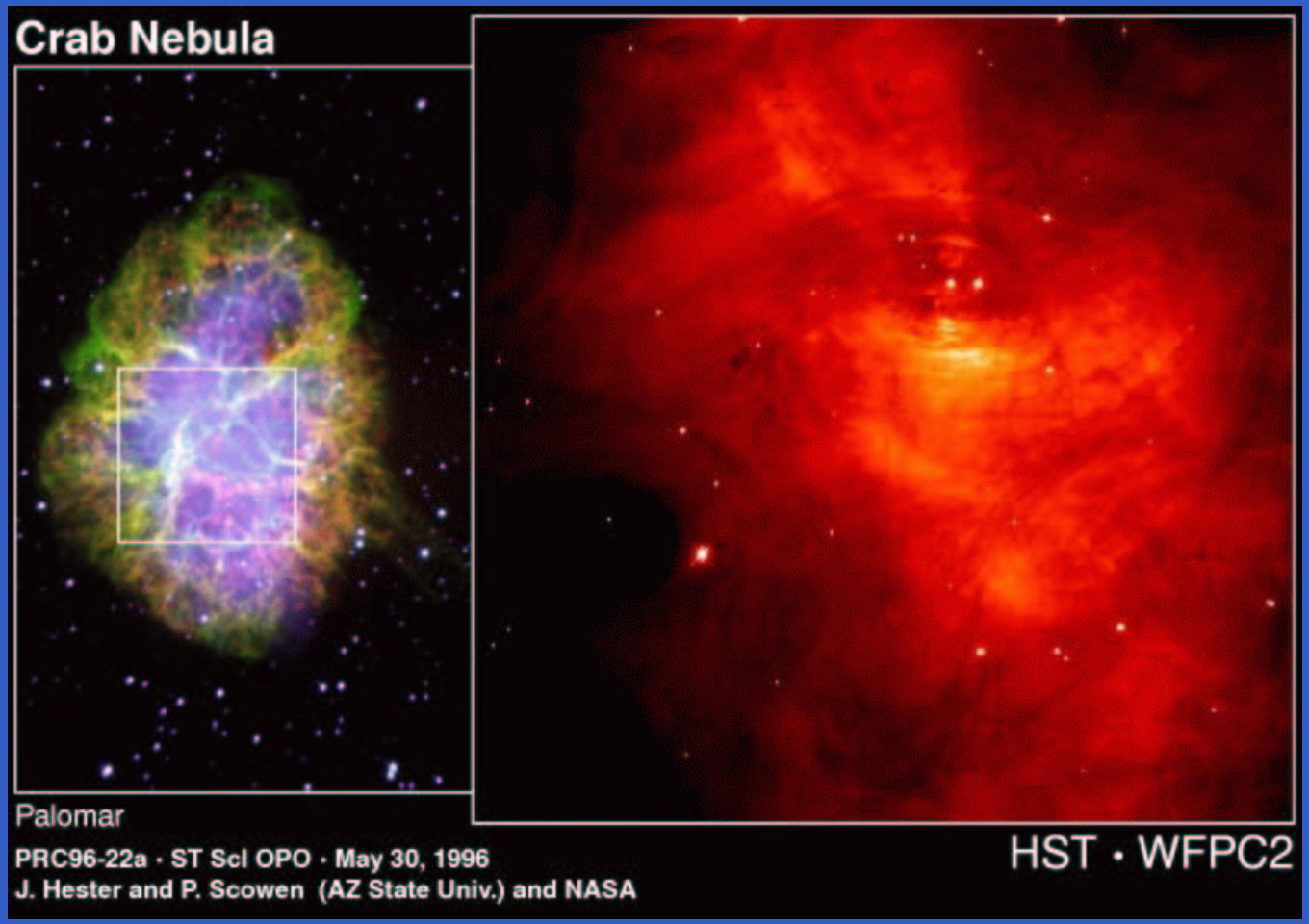
Phase Diagram of QCD



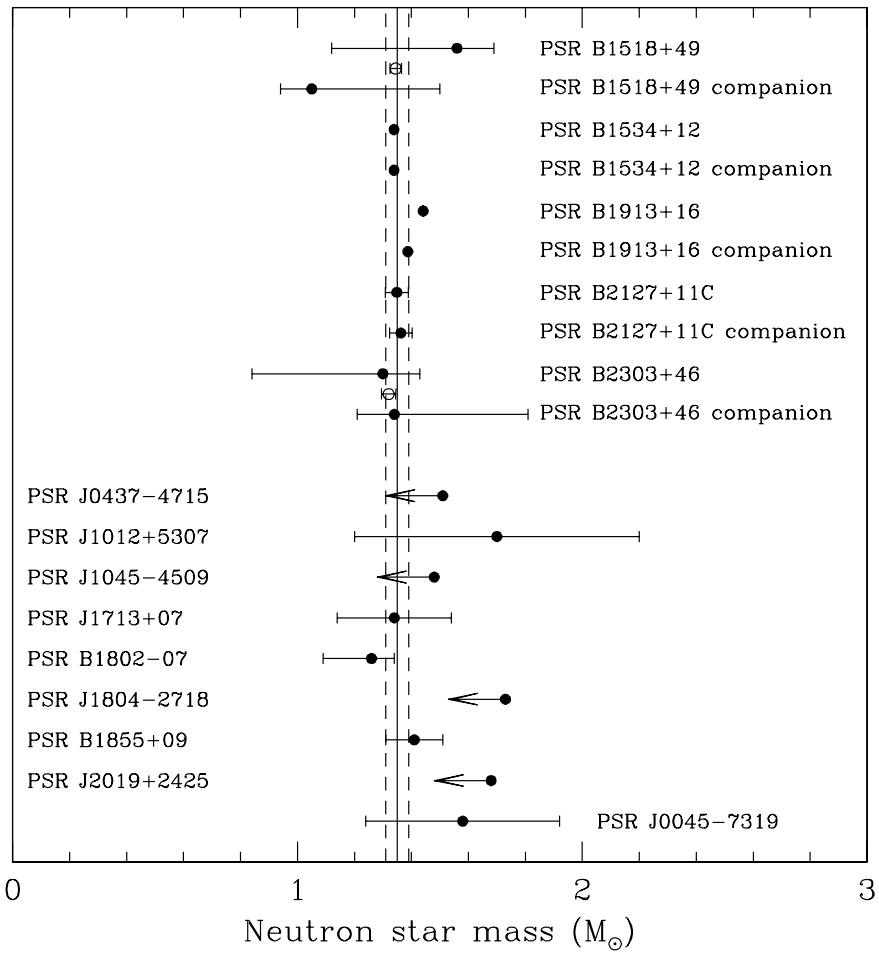
- Early universe at zero density and high temperature
- neutron star matter at zero temperature and high density
- lattice gauge simulations at $\mu = 0$:
  phase transition at $T_c \approx 170$ MeV

Neutron Stars



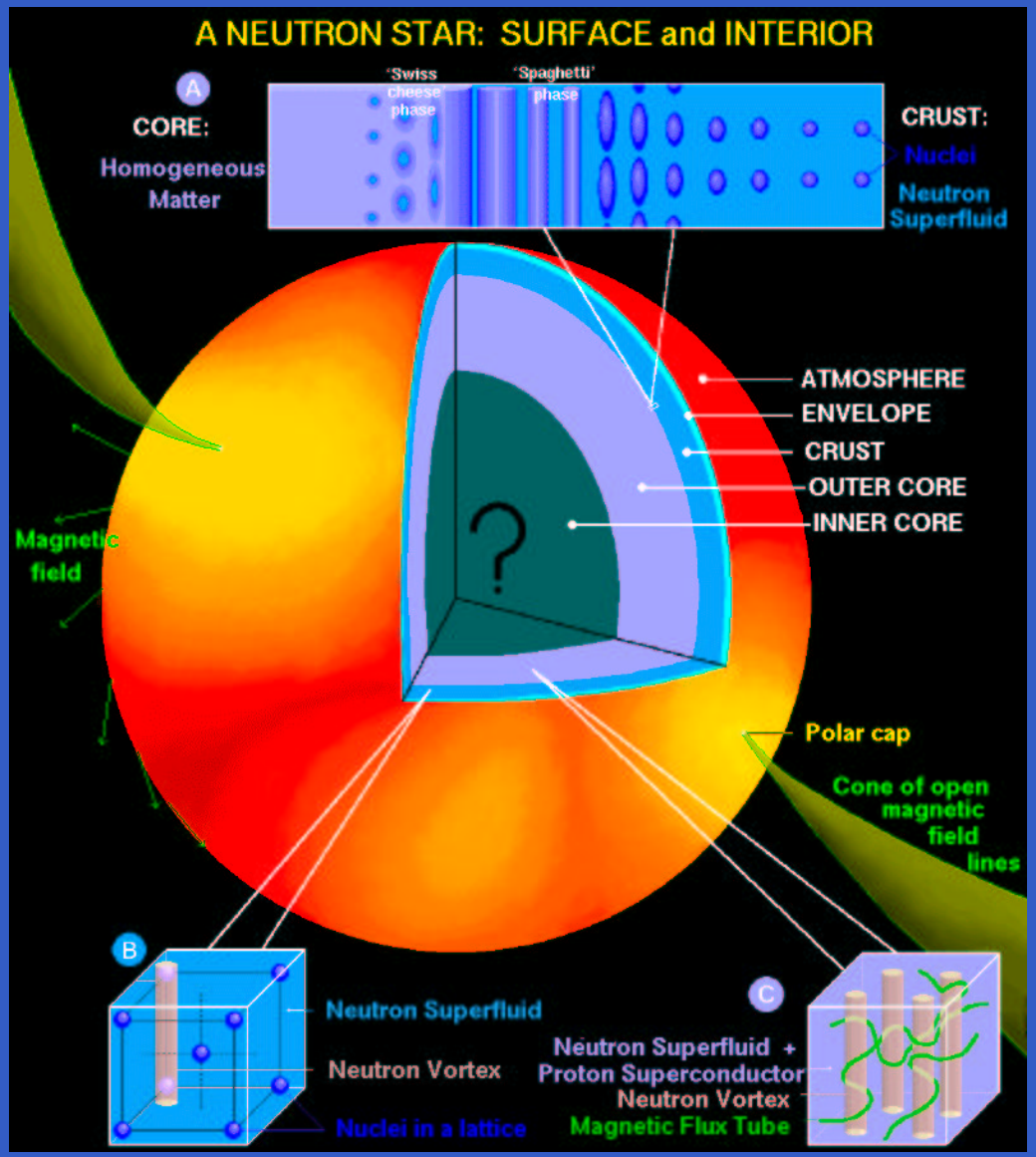
- produced in supernova explosions (type II)
- compact, massive objects: radius $\approx$ 10 km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3

Masses of Pulsars (Thorsett and Chakrabarty (1999))



- more than 1500 pulsars known
- best determined mass: $M = (1.4411 \pm 0.00035) M_\odot$ (Hulse-Taylor-Pulsar)
- shortest rotation period: 1.557 ms (PSR 1937+21)

Structure of Neutron Stars — the Crust (Dany Page)



- $n \leq 10^4$ g/cm^3: atmosphere (atoms)

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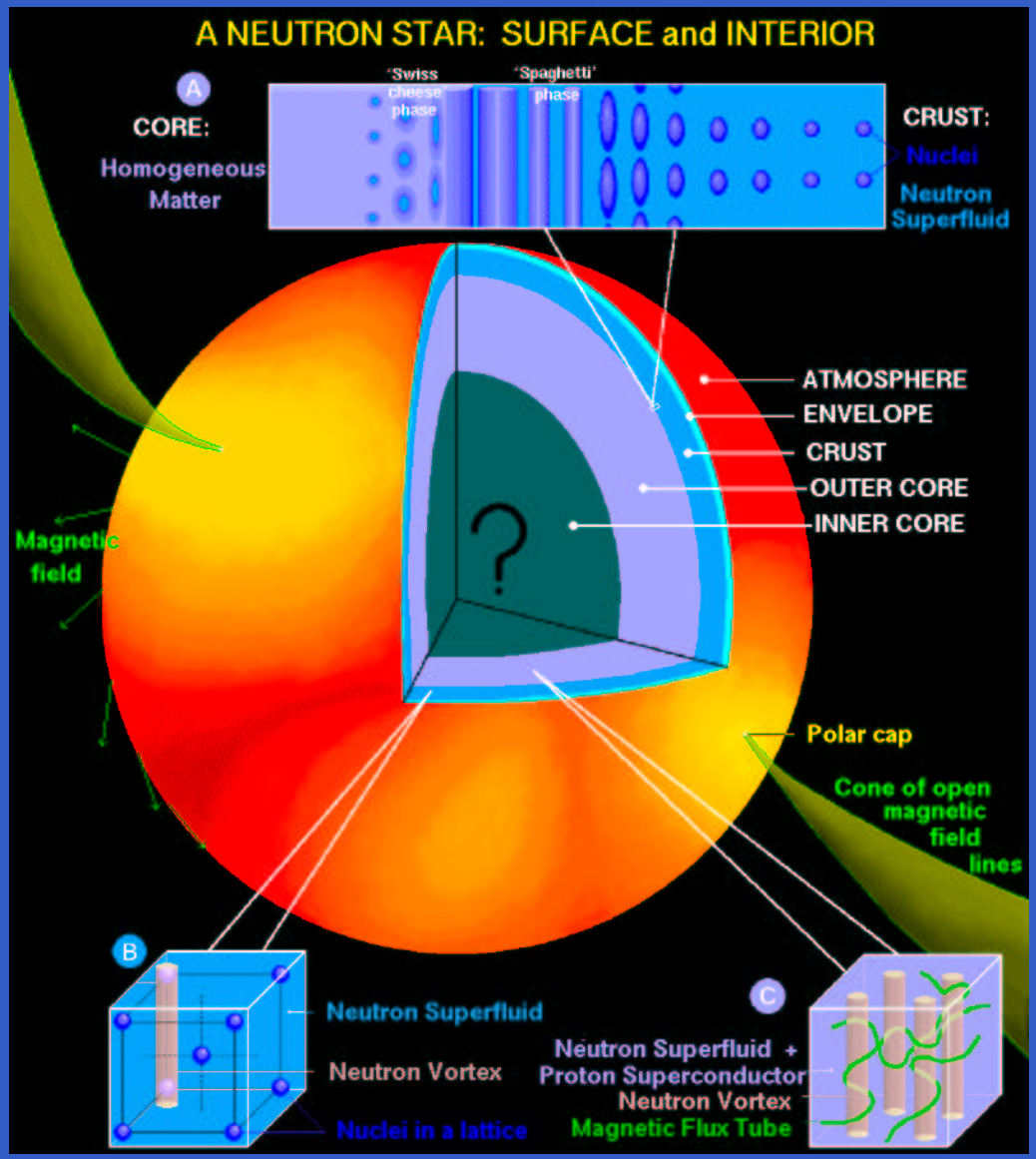

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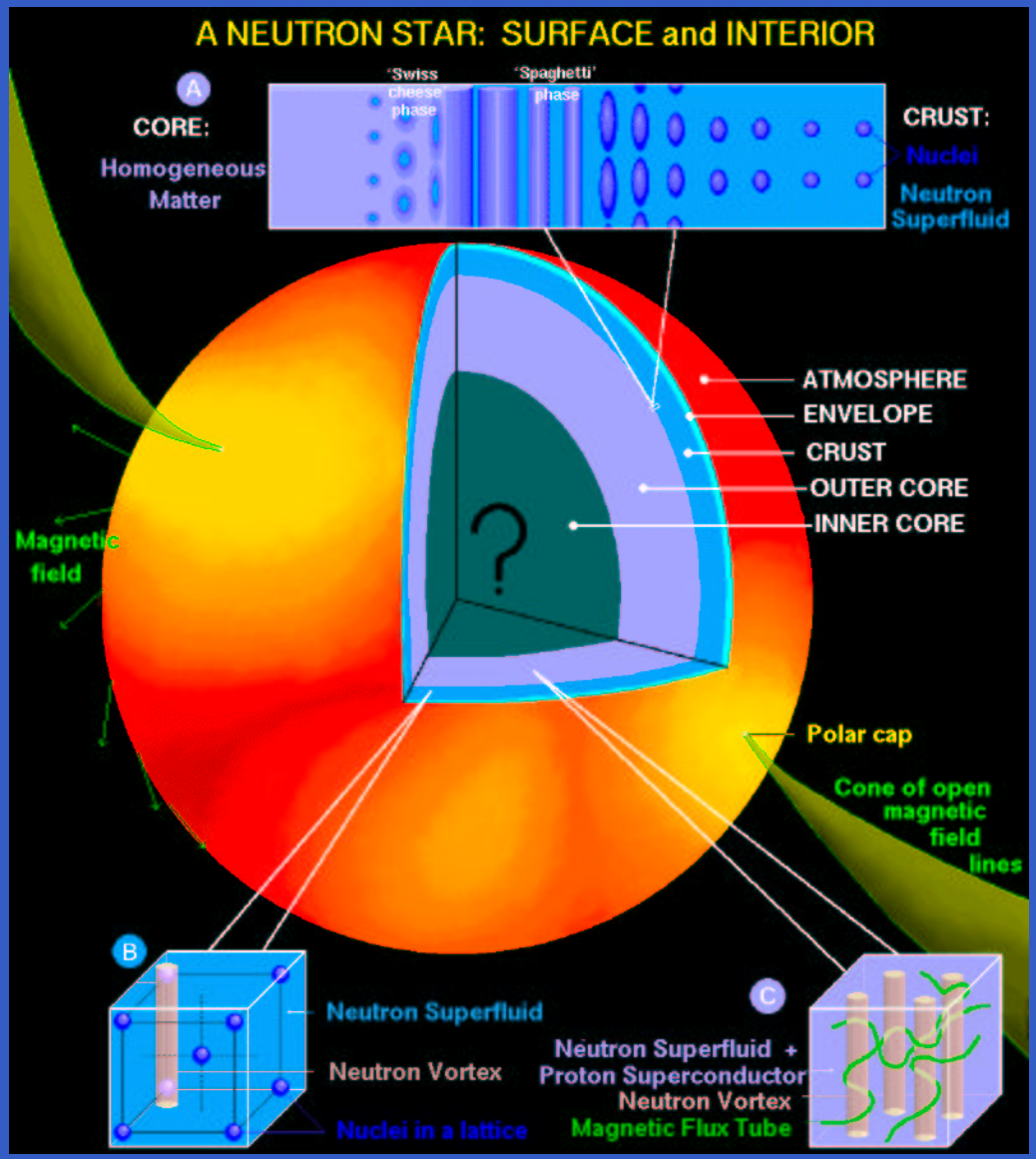

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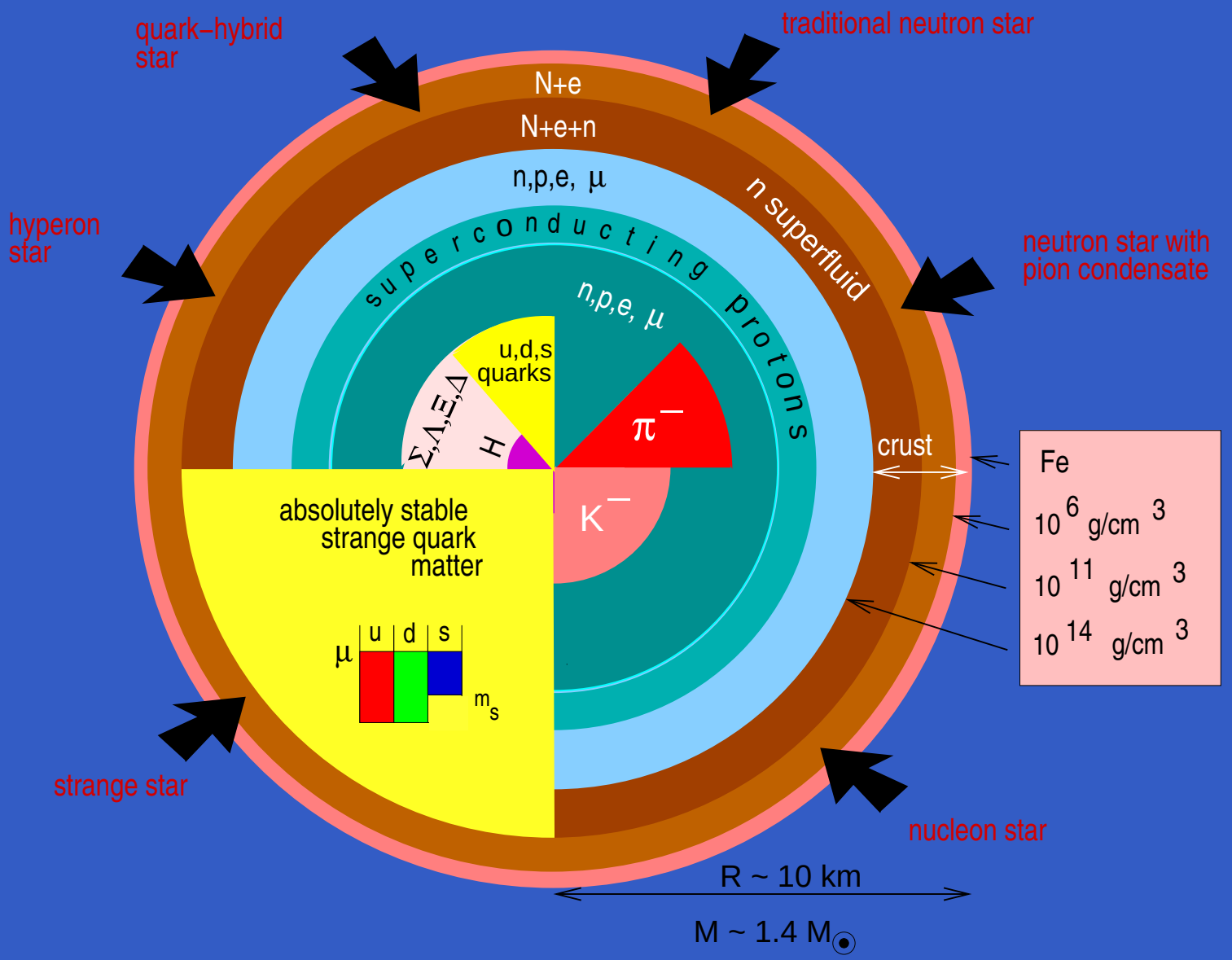
- $n = 10^4 - 4 \cdot 10^{11}$ g/cm^3: outer crust or envelope (free e^-, lattice of nuclei)
- $n = 4 \cdot 10^{11} - 10^{14}$ g/cm^3: Inner crust (lattice of nuclei with free neutrons and e^-)

Structure of a Neutron Star — the Core (Fridolin Weber)



Neutron Star Matter for a Free Gas

(Ambartsumyan and Saakyan, 1960)

Hadron	p,n	Σ^-	Λ	others
appears at:	$\ll n_0$	$4n_0$	$8n_0$	$> 20n_0$

but the corresponding equation of state results in a maximum mass of only

$$M_{\max} \approx 0.7 M_\odot < 1.44 M_\odot$$

(Oppenheimer and Volkoff, 1939)

$\Longrightarrow$ effects from strong interactions are essential to describe neutron stars!

Neutron Star Modelling

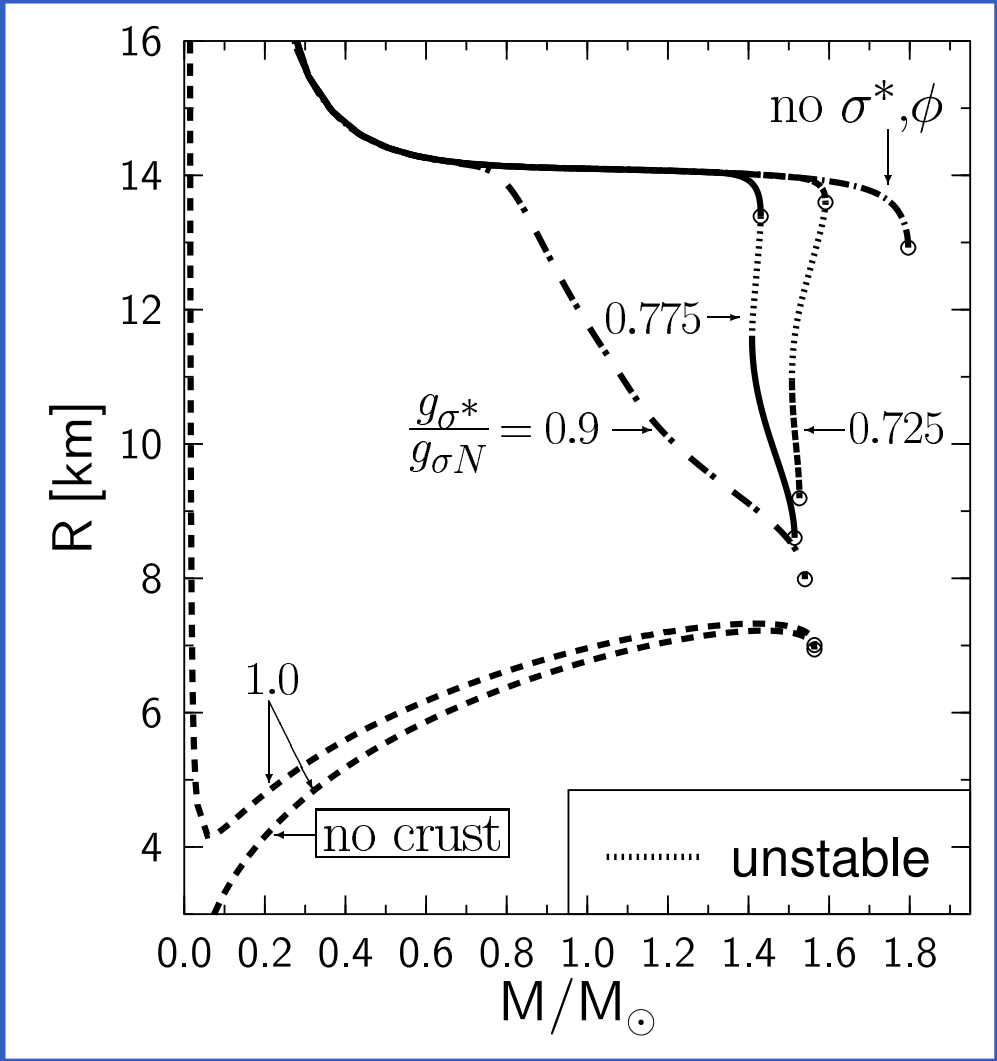
Neutron Star Matter and Hyperons

Hyperons appear at $n \approx 2n_0$!
(based on hypernuclear data!)

- nonrelativistic potential model (Balberg and Gal, 1997)
- quark-meson coupling model (Pal et al., 1999)
- relativistic mean–field models (Glendenning, 1985; Knorren, Prakash, Ellis, 1995; JS and Mishustin, 1996)
- relativistic Hartree–Fock (Huber, Weber, Weigel, Schaab, 1998)
- Brueckner–Hartree–Fock (Baldo, Burgio, Schulze, 2000; Vidana et al., 2000)
- chiral effective Lagrangian's (Hanauske et al., 2000)
- density-dependent hadron field theory (Hofmann, Keil, Lenske, 2001)

$\Rightarrow$ neutron stars are strange !!!

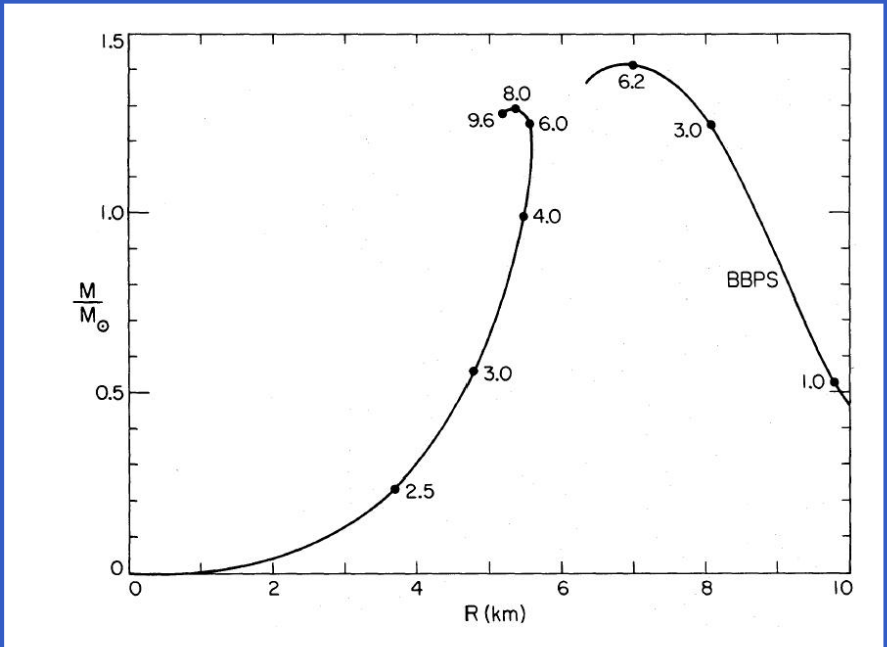
Ultracompact Neutron Stars with Hyperons — Hyperon Stars



(JSB, Hanauske, Stöcker, Greiner, PRL 89, 171101 (2002))

- new stable solution in the mass–radius diagram!
- neutron star twins: $M_{\rm hyp} \sim M_n$ but $R_{\rm hyp} < R_n$
- selfbound compact stars for strong attraction with $R = 7 - 8$ km

Selfbound Star versus Neutron Star



selfbound stars:

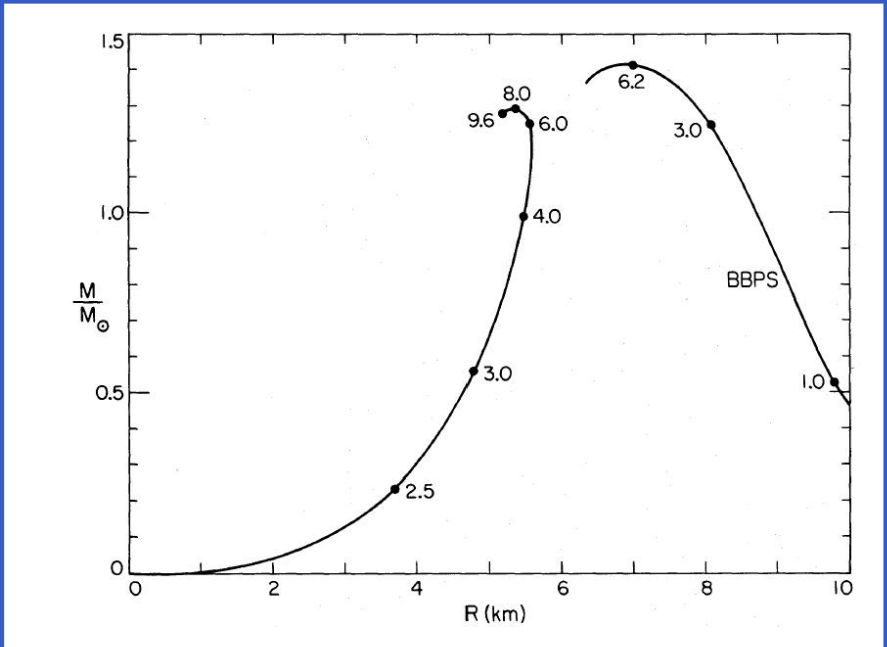
- vanishing pressure at a finite energy density
- mass-radius relation starts at the origin (ignoring a possible crust)
- arbitrarily small masses and radii possible

neutron stars:

- bound by gravity, finite pressure for all energy density
- mass-radius relation starts at large radii
- minimum neutron star mass: $M \sim 0.1 M_\odot$ with $R \sim 200$ km

Selfbound Star versus Neutron Star

(Hartle, Sawyer, Scalapino (1975!))



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similar masses and radii, cooling, surface (crust), . . . but look for

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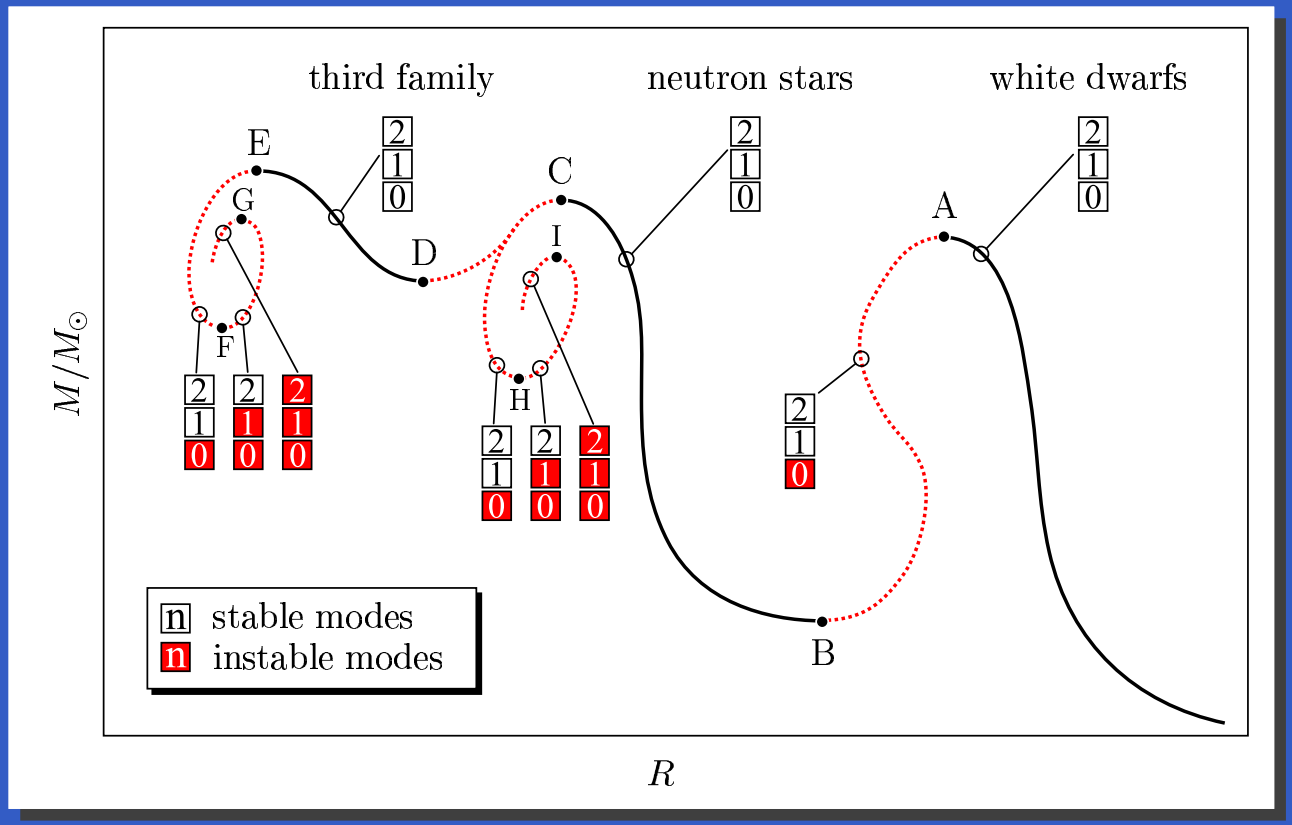
Third Family of Compact Stars



(Schertler, Greiner, JSB, Thoma (2000))

- third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!
- generates stars more compact than neutron stars
- possible for any first order phase transition!

Signals for a Third Family/Phase Transition?

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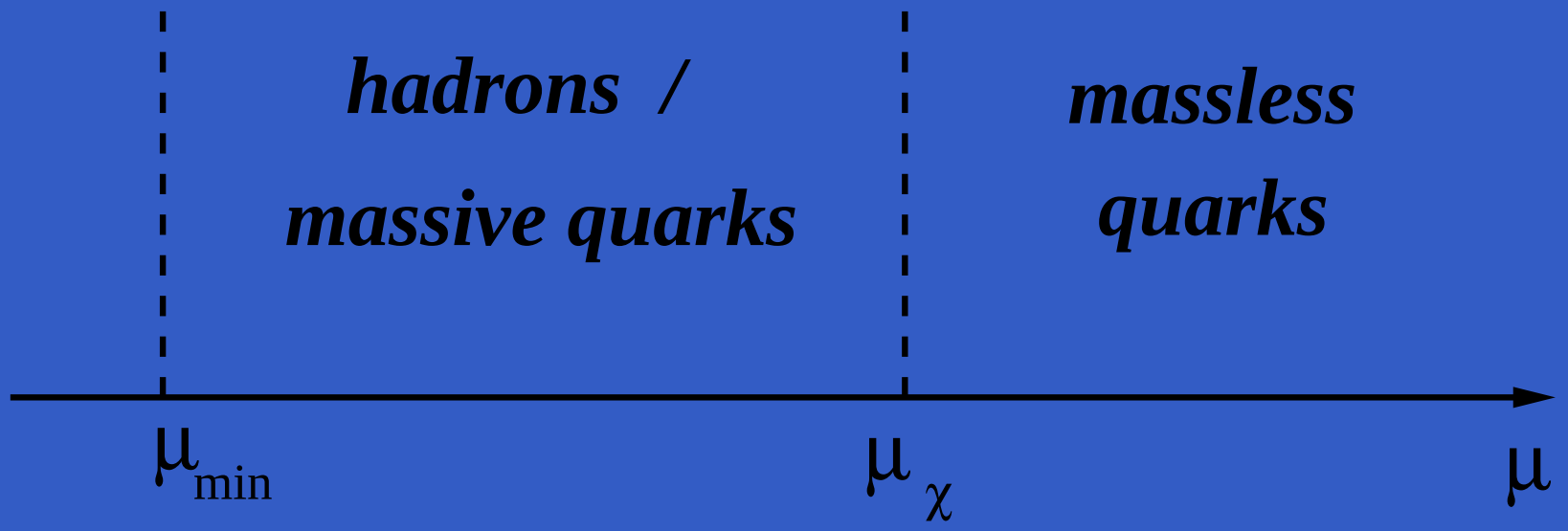
The Third Family: Quark Stars, Hyperon Stars . . .

- MIT bag model (Glendenning and Kettner, 2000)
- massive quasi-particles of quarks (Schertler, C. Greiner, JSB, Thoma, 2000)
- interacting quarks in pQCD (Fraga, JSB, Pisarski, 2001)
- Kaon condensate (Banik and Bandyopadhyay, 2001)
- Hyperon Matter (JSB, Hanauske, Stöcker, W. Greiner, 2002)
- MIT bag model (Mishustin, Hanauske, Bhattacharyya, Satarov, Stöcker, W. Greiner, 2003)
- color-superconducting quarks (Banik and Bandyopadhyay, 2003)
- MIT bag and rotation (Bhattacharyya, Ghosh, Hanauske, Raha, 2004)
- Kaon condensate, quarks and rotation (Banik, Hanauske, Bandyopadhyay, W. Greiner, 2004)

notes

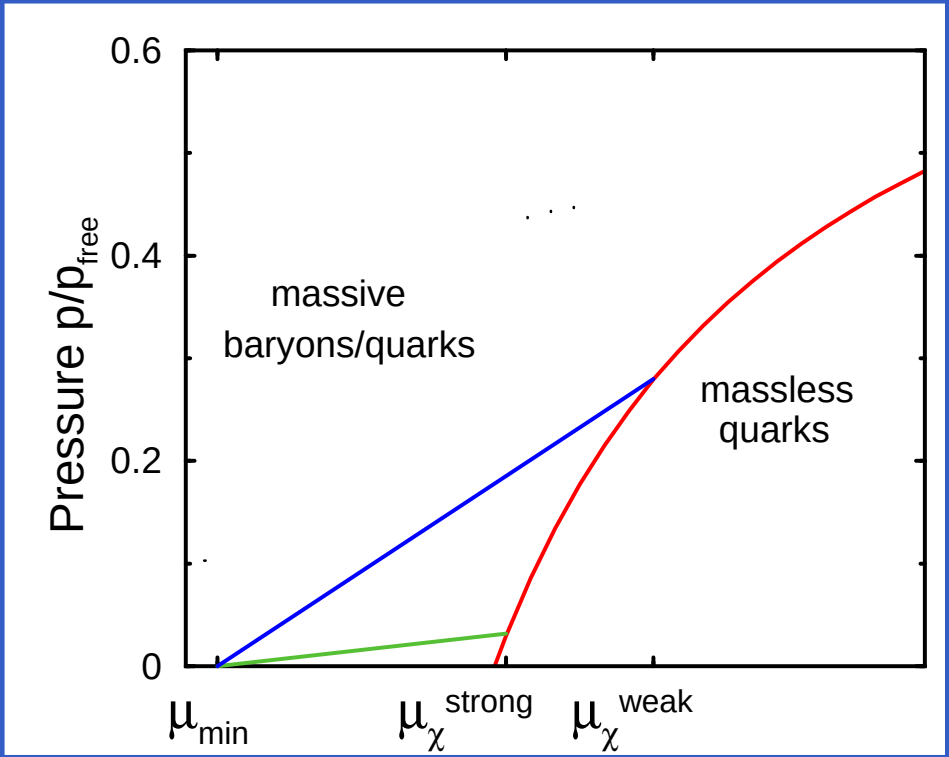
A Model For Cold And Dense QCD



Two possibilities for first-order chiral phase transition:

- A weakly first-order chiral transition (or no true phase transition),
  $\Longrightarrow$ one type of compact star (neutron star)
- A strongly first-order chiral transition
  $\Longrightarrow$ two types of compact stars:
  a new stable solution with smaller masses and radii

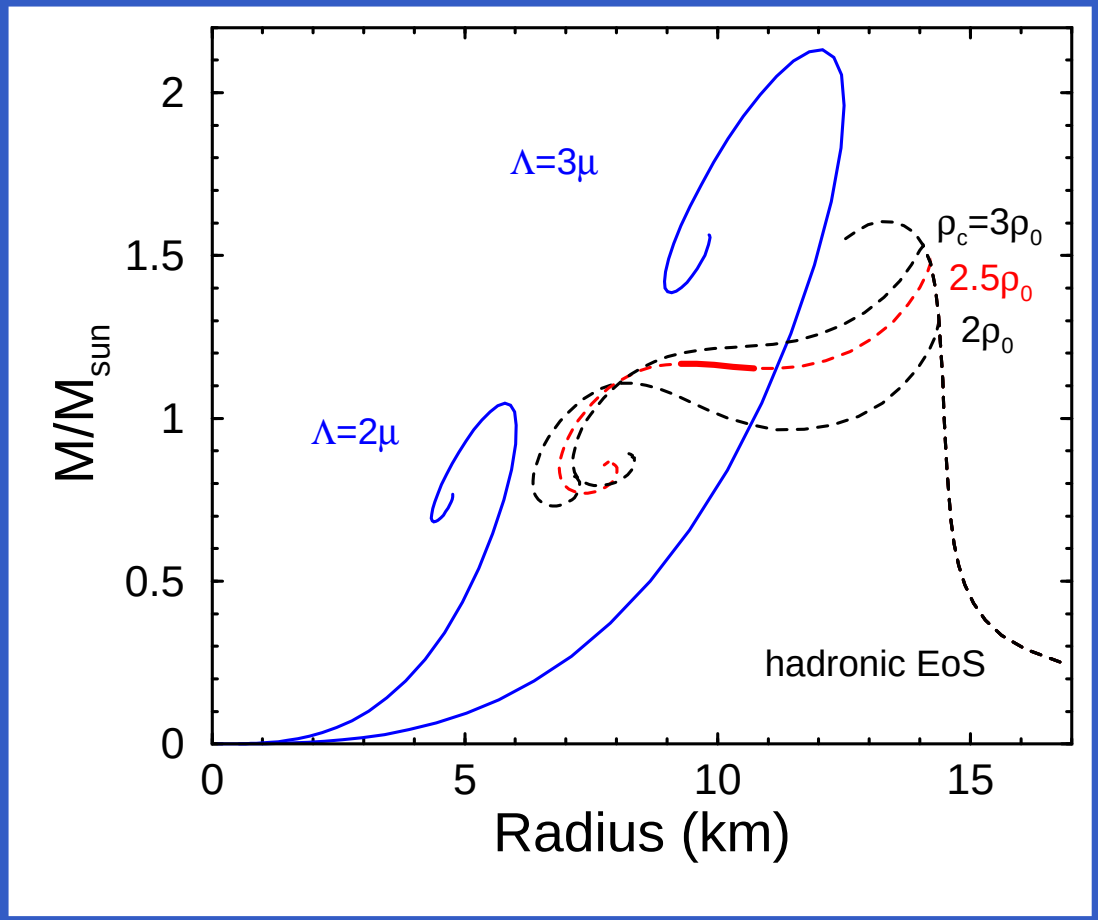
The two possible scenarios



- Weak: phase transition is weakly first order or a crossover $\rightarrow$ pressure in massive phase rises strongly
- Strong: transition is strongly first order $\rightarrow$ pressure rises slowly with μ
- asymmetric matter up to $\sim 2n_0$: [Akmal,Pandharipande,Ravenhall (1998)]

$$E/A \sim 15 \text{ MeV } (n/n_0) \rightarrow p_B \sim 0.04 \left(\frac{n}{n_0}\right)^2 \left(\frac{m_q}{\mu}\right)^4 \cdot p_{\text{free}}$$

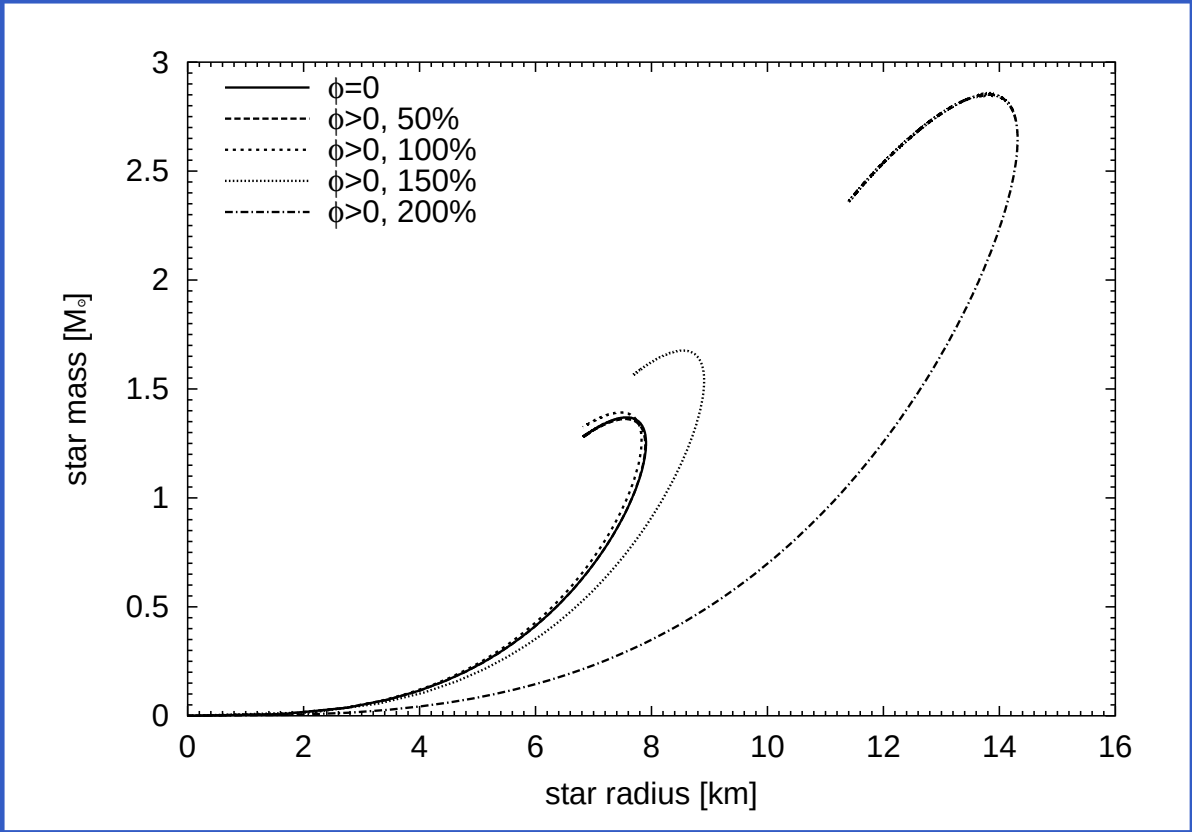
Quark star twins? (Fraga, JSB, Pisarski (2001))



blue curves: pQCD calculation

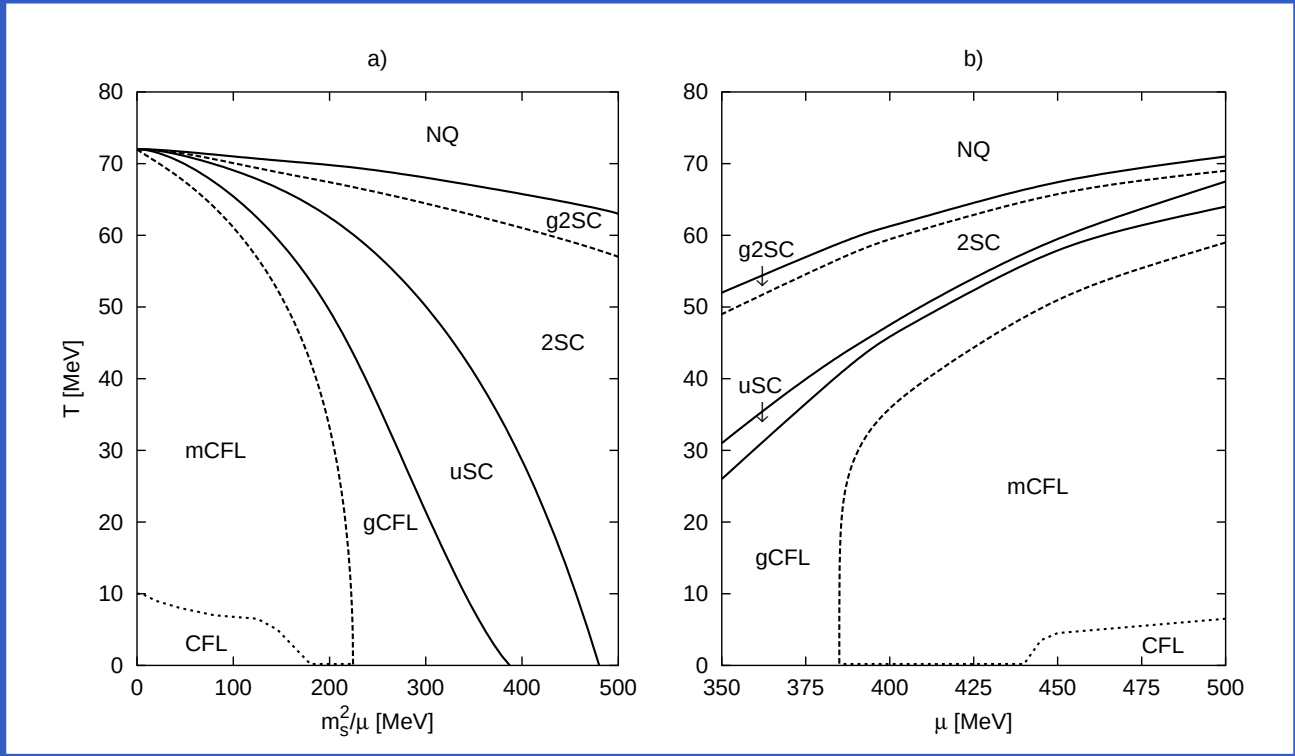
- Weak transition: ordinary neutron star with quark core (hybrid star)
- Strong transition: third class of compact stars possible with maximum masses $M \sim 1\, M_\odot$ and radii $R \sim 6$ km
- Quark phase dominates ($n \sim 15\, n_0$ at the center), small hadronic mantle

Massive Quark Stars? (Rüster and Rischke (2004))



- quark star with color–superconducting quarks
- uses NJL model for pairing quarks
- increased interactions gives massive quark stars
- massive quark stars also for HDL calculation (Strickland and Andersen (2002))

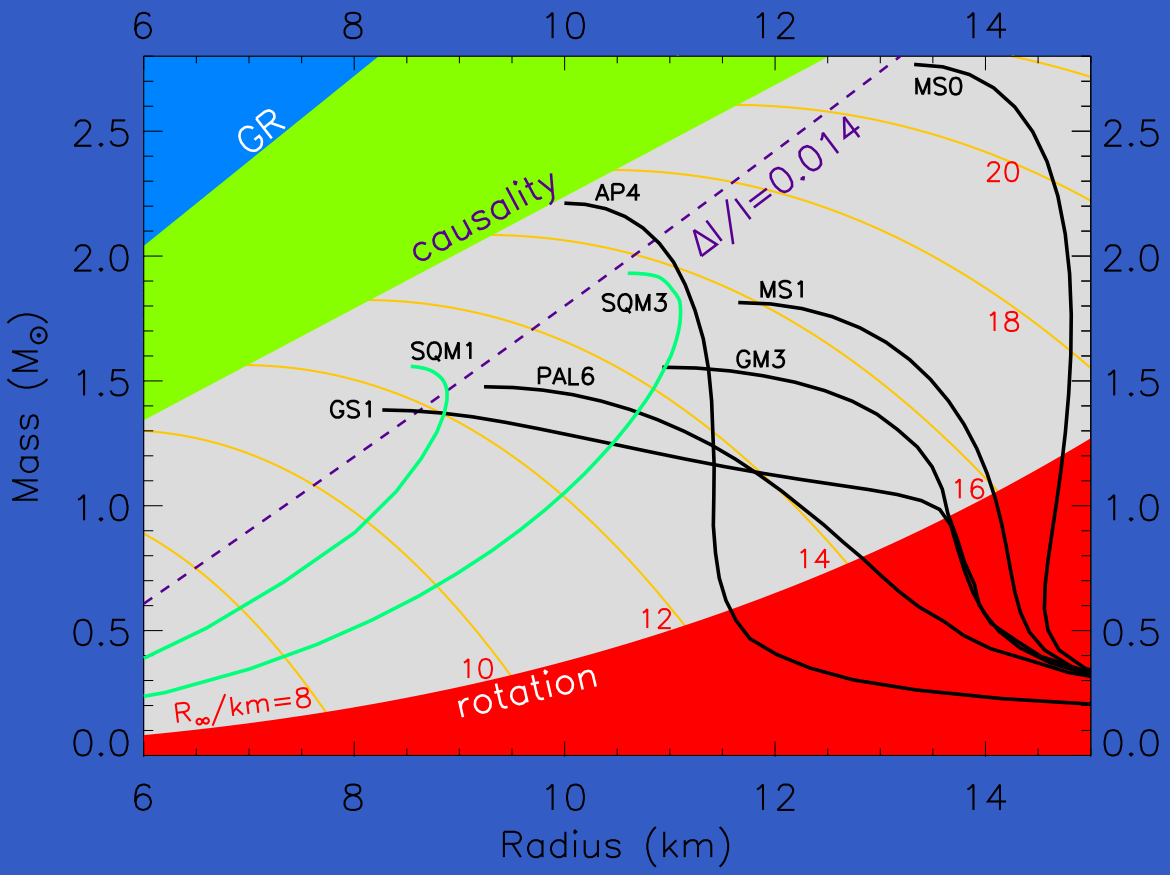
Phases in Strange Quark Matter (Rüster, Shovkovy, Rischke (2004))



- phases of color superconducting quark matter in β equilibrium
- two-flavor color superconducting phase (2SC), gapless 2SC phase, only up quarks pair (uSC)
- color-flavor locked phase (CFL), gapless CFL phase, metallic CFL phase
- normal (unpaired) quark matter (NQ) only at large temperatures
- important for newly born, hot proto-neutron stars!

Neutron Star Data

Constraints on the Mass–Radius Relation

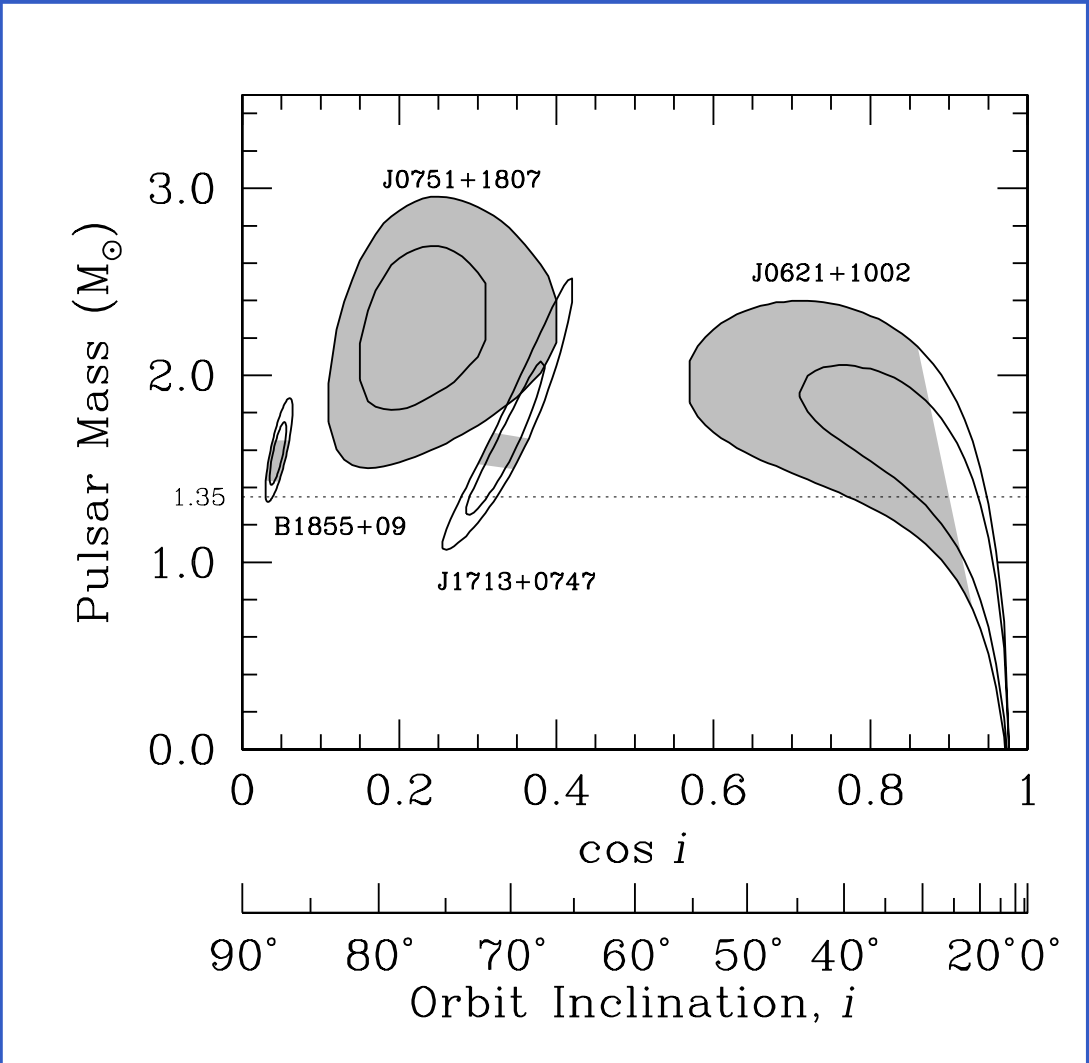


(Lattimer and Prakash (2004))

- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- observed giant glitch from Vela pulsar: moment of inertia changes by 1.4
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$

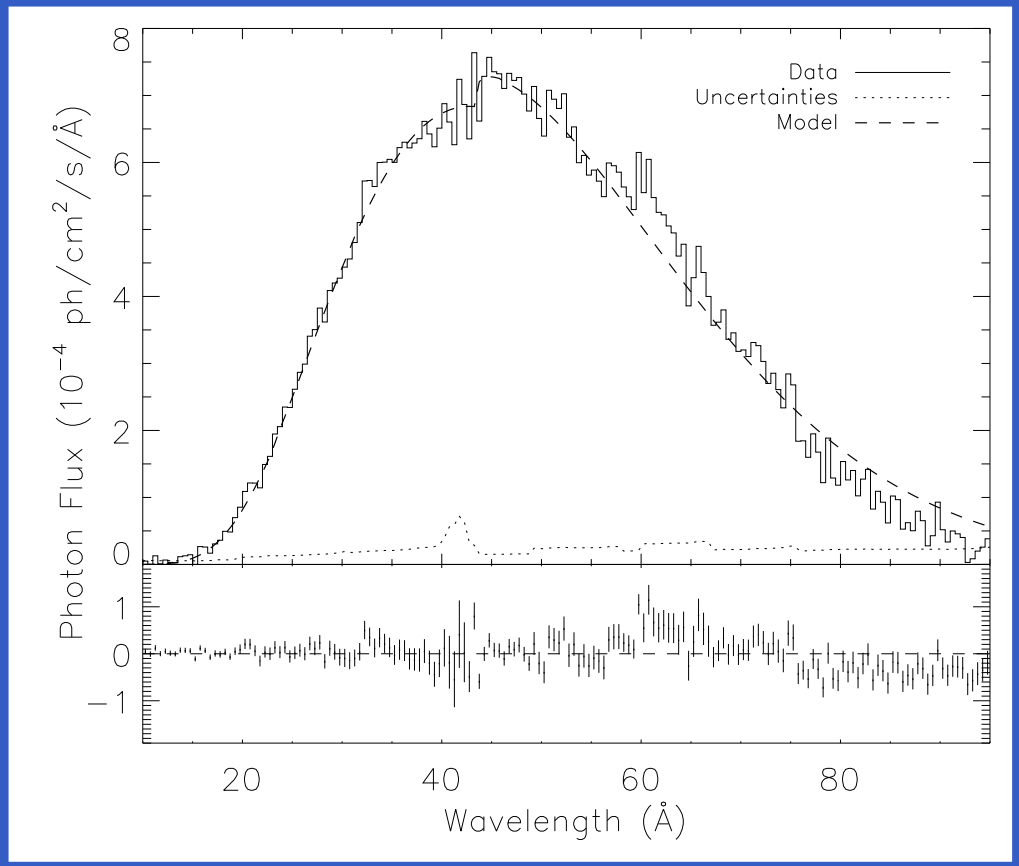
Heavy Neutron Stars in Pulsar–White Dwarfs Systems?

(Nice, Splaver, Stairs (2003))



- four pulsars with a white dwarf companion
- measure masses by changes in the pulsar signal
- shaded area: from theoretical limits for white–dwarf companion
- massive pulsar J0751+1807: $M = 1.6 - 2.8 M_\odot$ (2σ!)
- independent of the inclination angle!

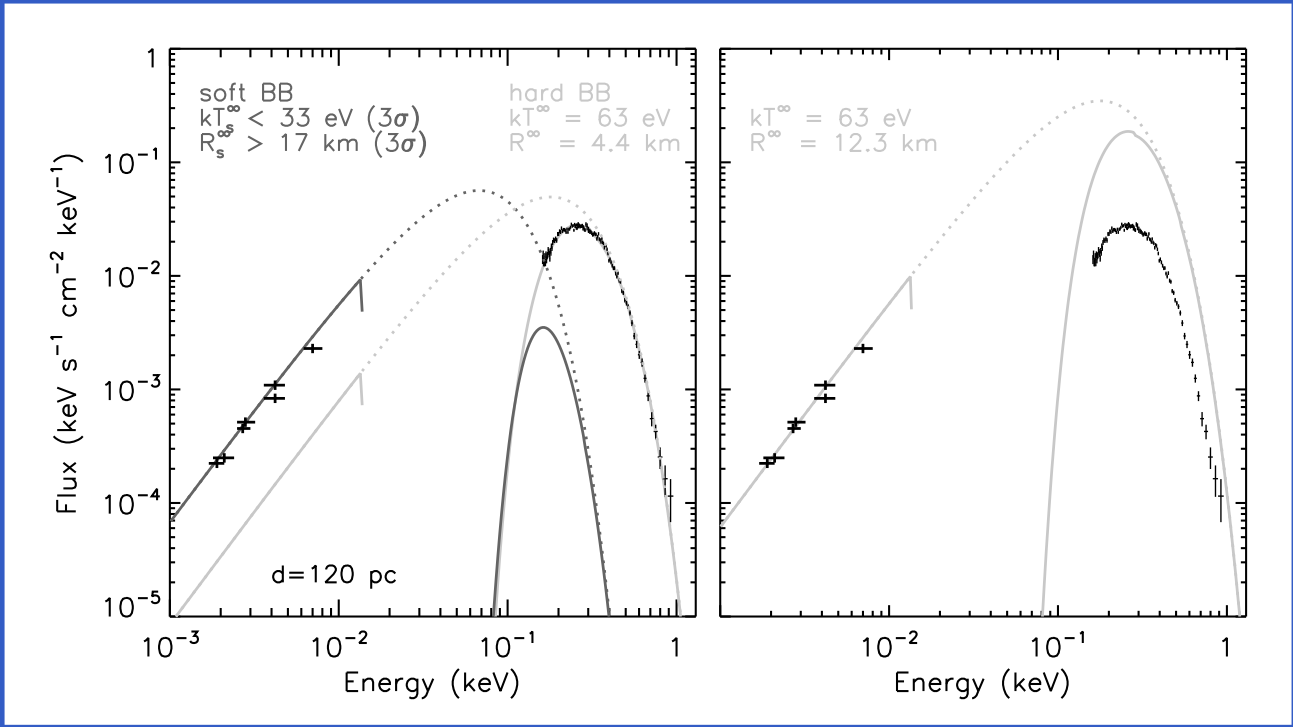
Isolated Neutron Star RX J1856



(Drake et al. (2002))

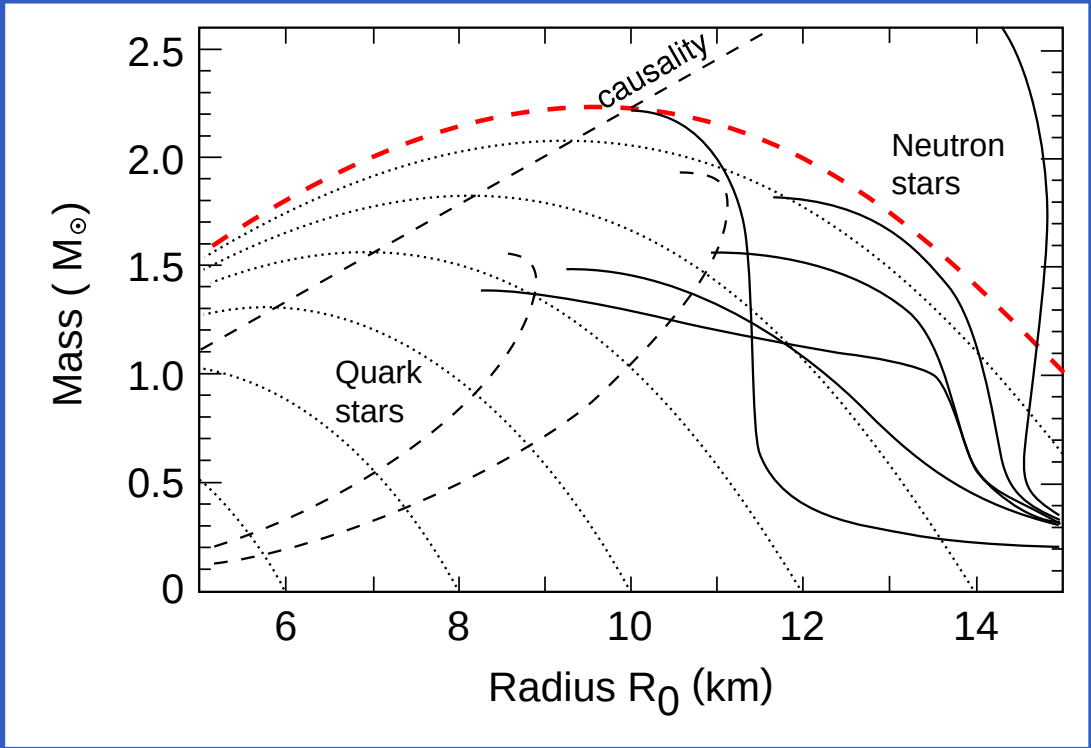
- closest known neutron star
- perfect black–body spectrum, no spectral lines!
- for black-body emission: $T = 60$ eV and $R_\infty = R\sqrt{1 - 2GM/R} = 4 - 8$ km!

Modeling the Atmosphere of Neutron Stars (Burwitz et al. (2003))



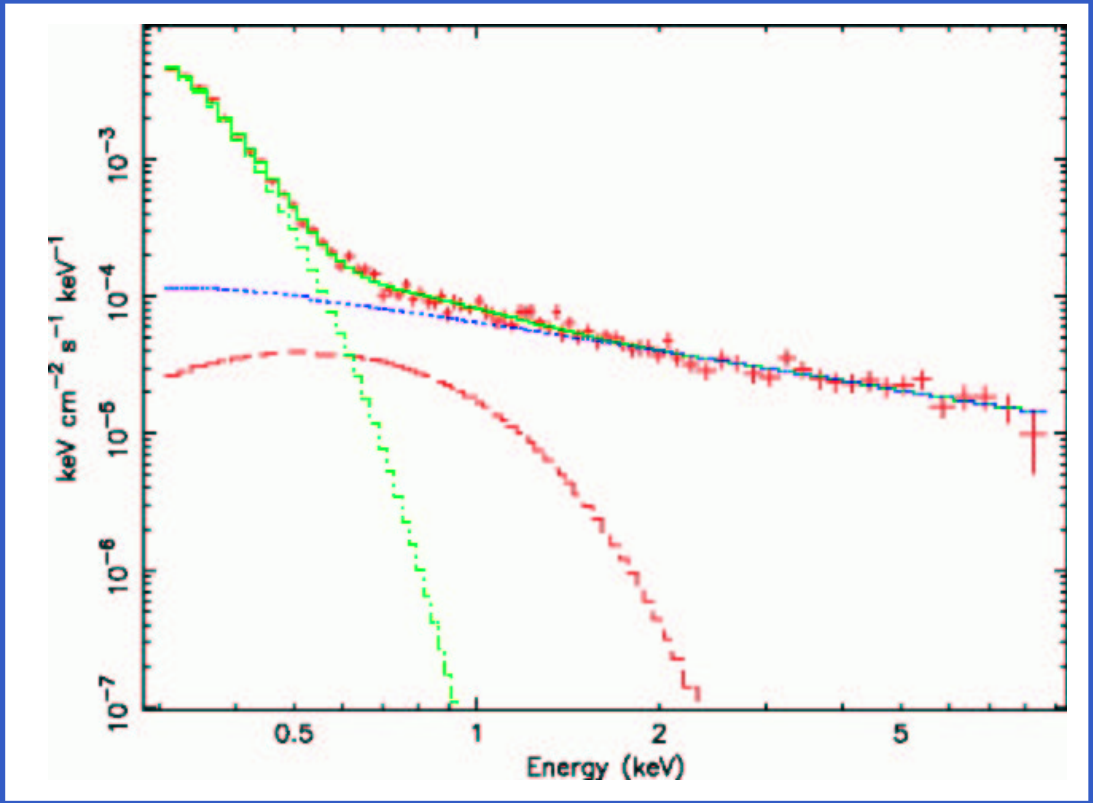
- H atmospheres ruled out, they over-predict the optical flux!
- heavy element atmospheres ruled out, as there are no spectral lines!
- all classic neutron star atmosphere models fail!
- alternatives: two-component blackbody model (left plot)
- or condensed matter surface for low $T < 86$ eV and high $B > 10^{13}$ G (right plot) — greybody with a suppression of a factor 7!

RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003))



- two-component blackbody: small soft temperature, so as not to spoil the x-ray band
- this implies a rather LARGE radius so that the optical flux is right!
- conservative lower limit: $R_\infty = 16.5$ km (d/117 pc)
- excludes quark stars and even neutron stars with a quark core!?

Spectra from Geminga (Caraveo et al. (2004))



- three component fit to spectra of the Geminga pulsar:

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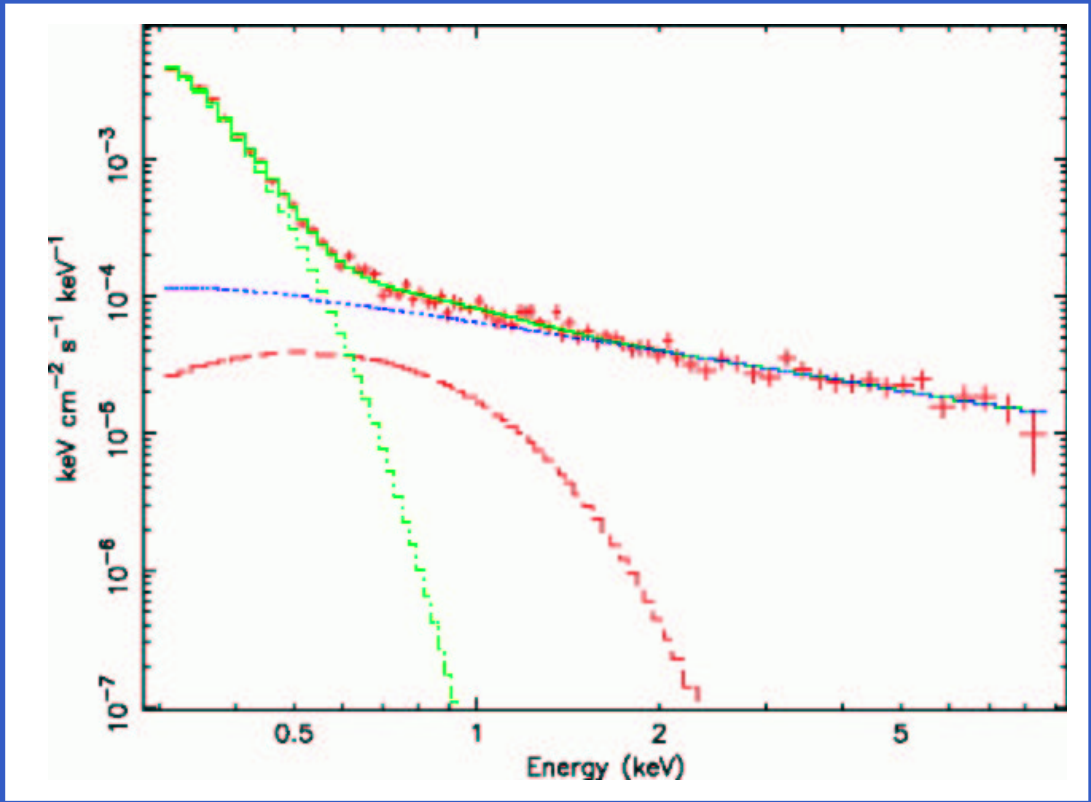

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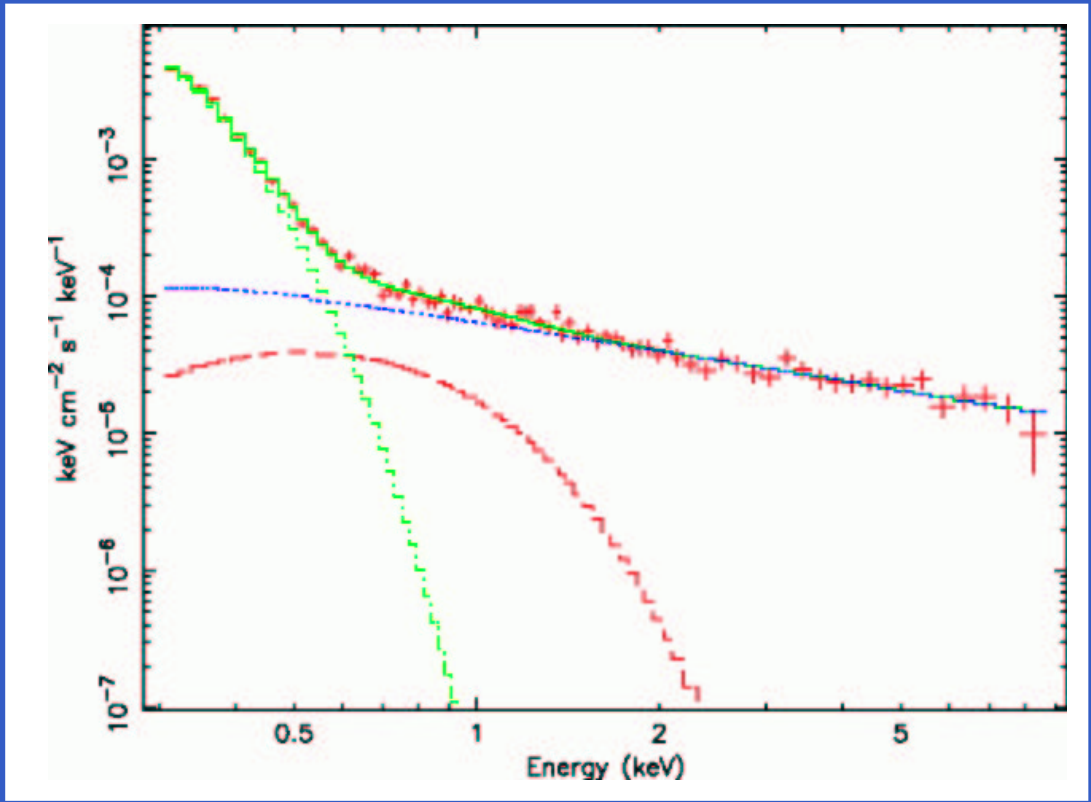

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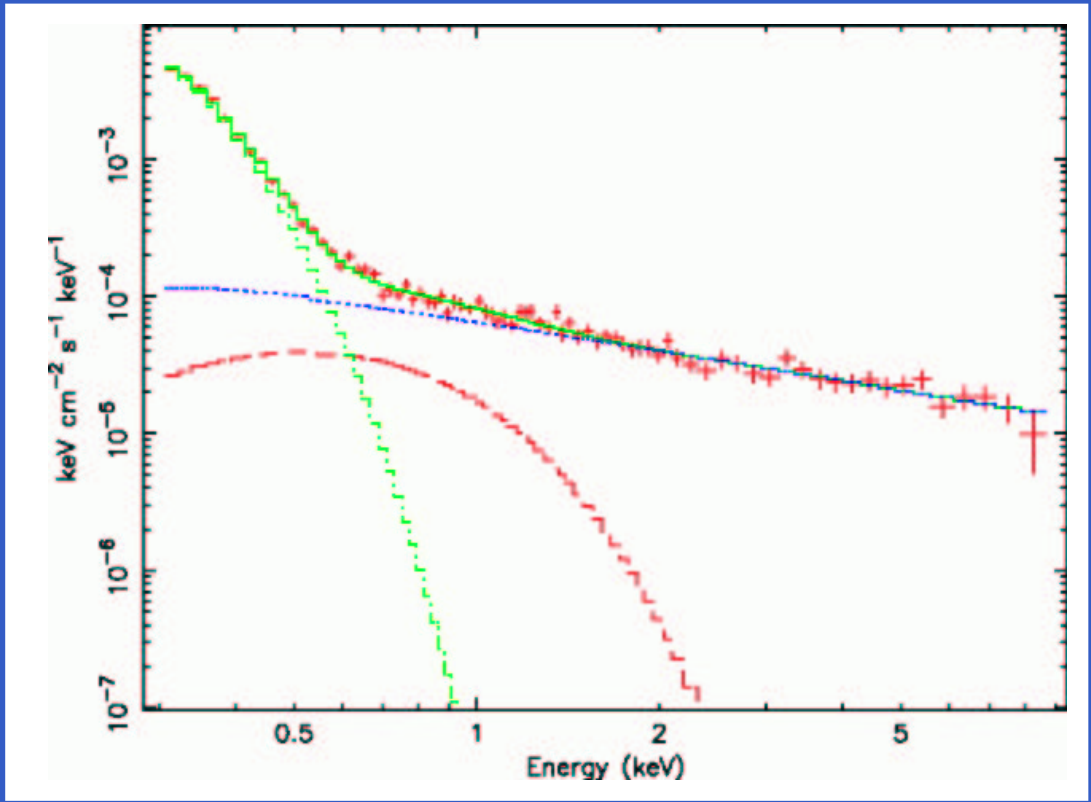
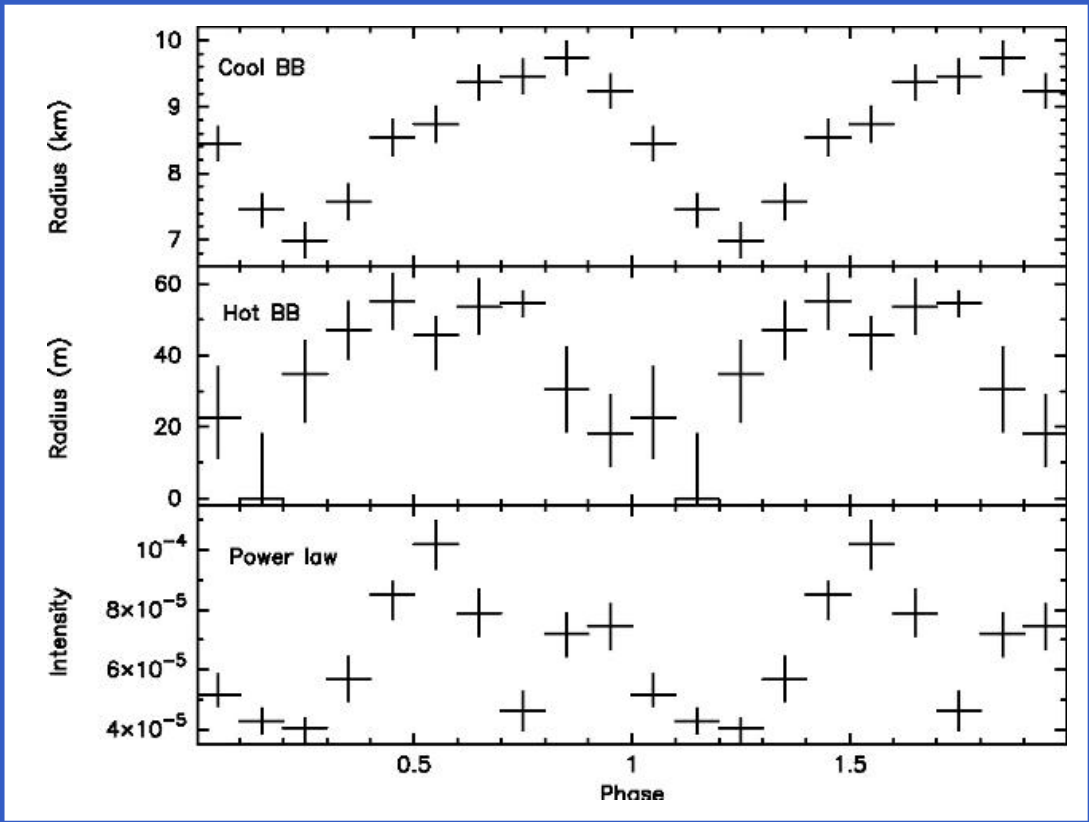


- three component fit to spectra of the Geminga pulsar:
- power law tail at high energies (from magnetosphere)
- hot black-body with a size of only $R = 40 \pm 10$ m (from polar caps)
- cool black-body with a size of $R = 8.6 \pm 1$ km (from pulsar surface?)

Phase Resolved Spectra from Geminga (Caraveo et al. (2004))



← power law flux at 1 keV

- power law tail at high energies (from magnetosphere)

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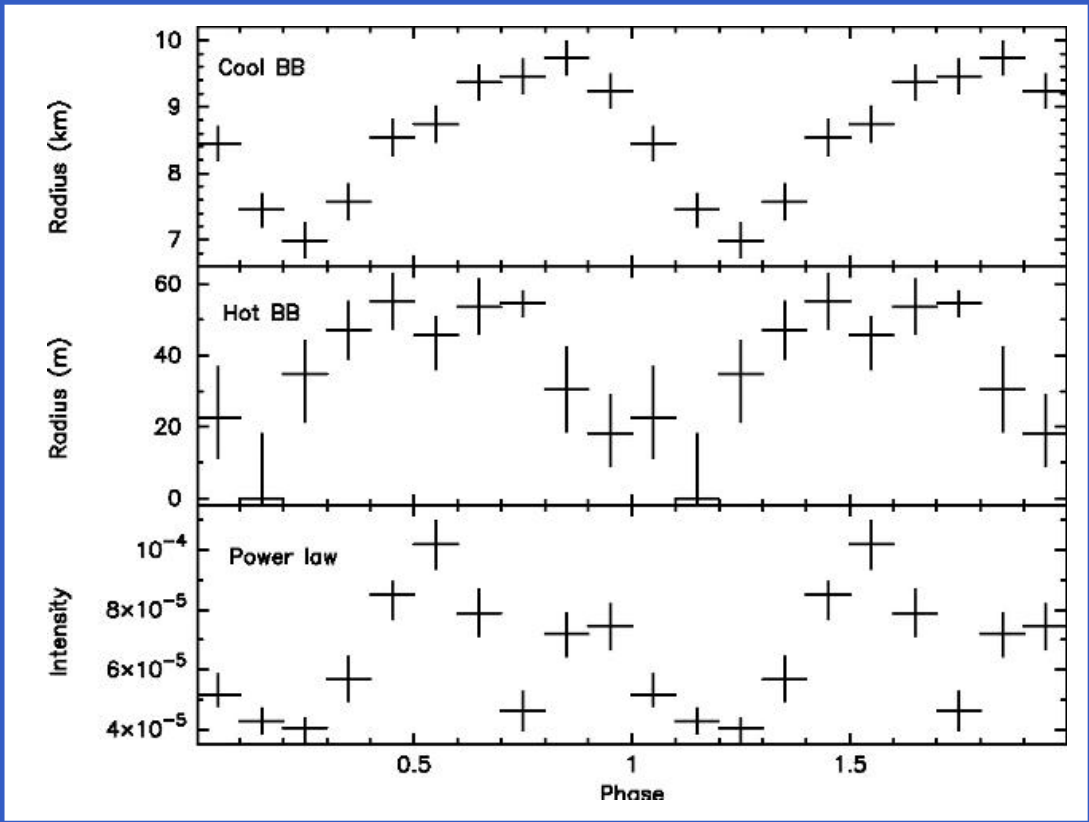

← radius of $T = 170$ eV hot spot (hot black–body)

← power law flux at 1 keV

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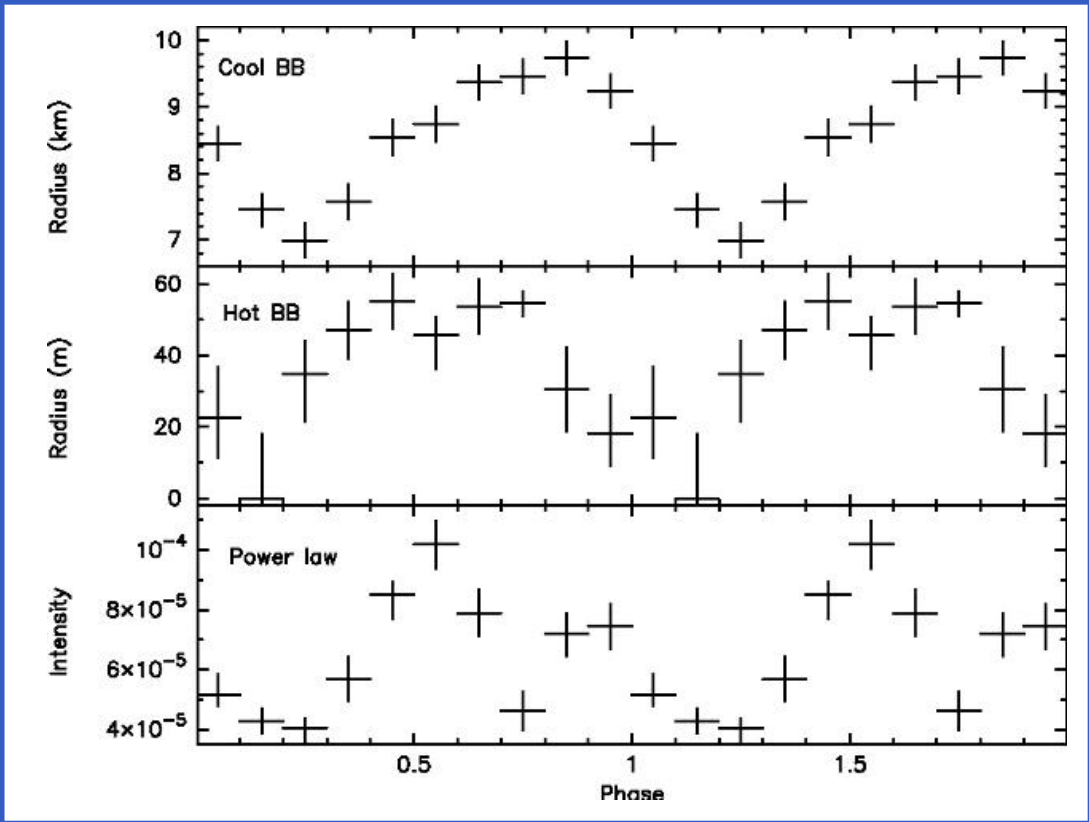


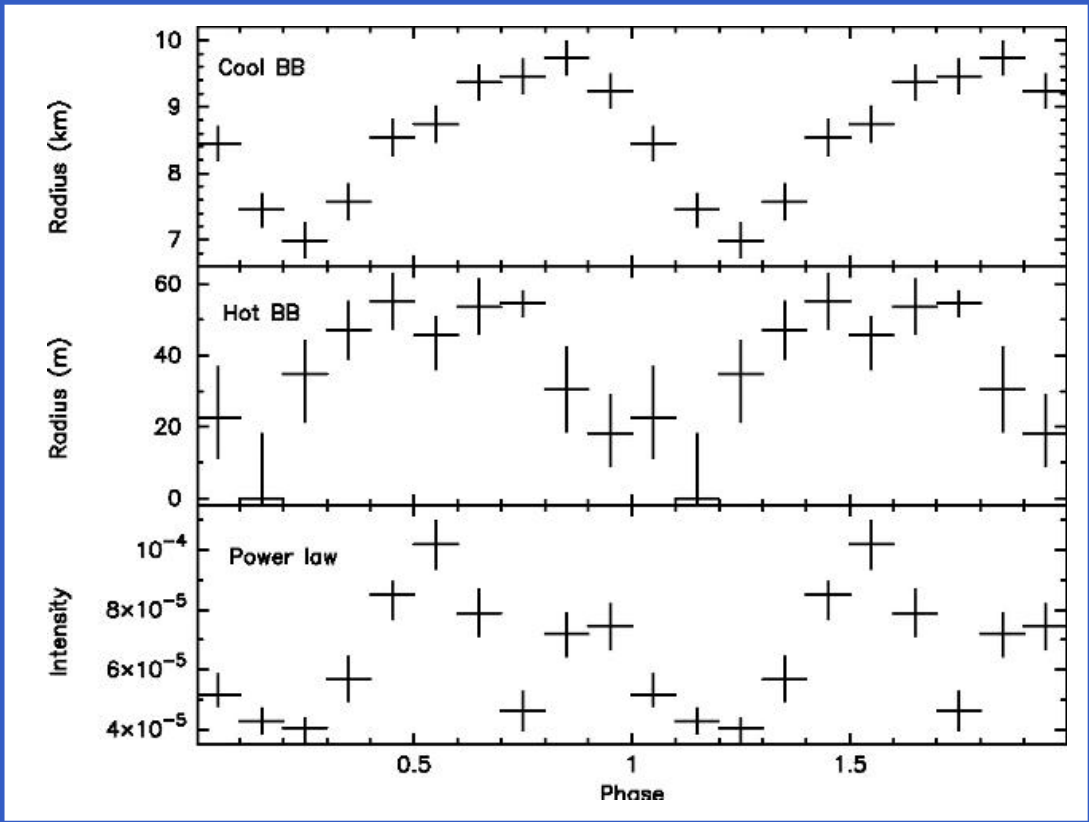
← radius of $T = 43$ eV emitting area (cool black–body)

← radius of $T = 170$ eV hot spot (hot black–body)

← power law flux at 1 keV

- power law tail at high energies (from magnetosphere)
- hot black-body with a size of only $R = 60$ m (from polar caps)
- cool black-body with a size of $R = 10$ km (from hot continent)

Phase Resolved Spectra from Geminga (Caraveo et al. (2004))



← radius of $T = 43$ eV emitting area (cool black–body)

← radius of $T = 170$ eV hot spot (hot black–body)

← power law flux at 1 keV

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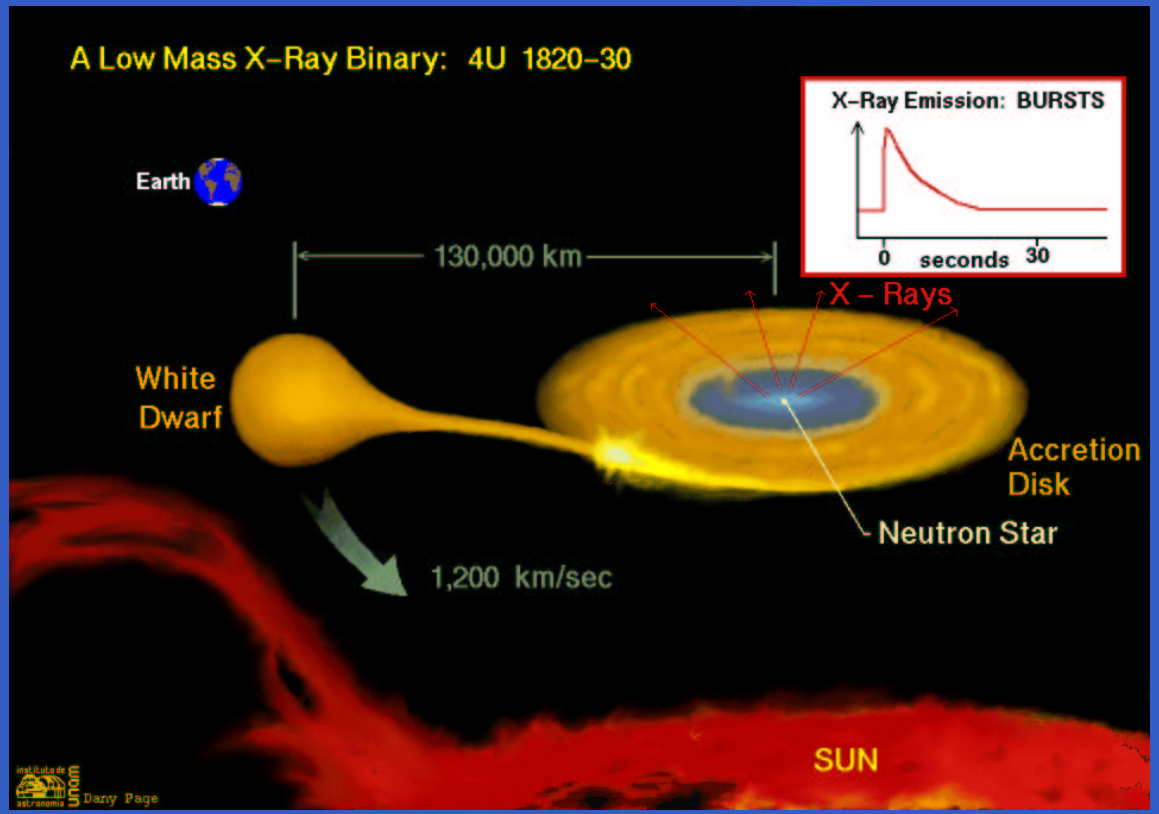
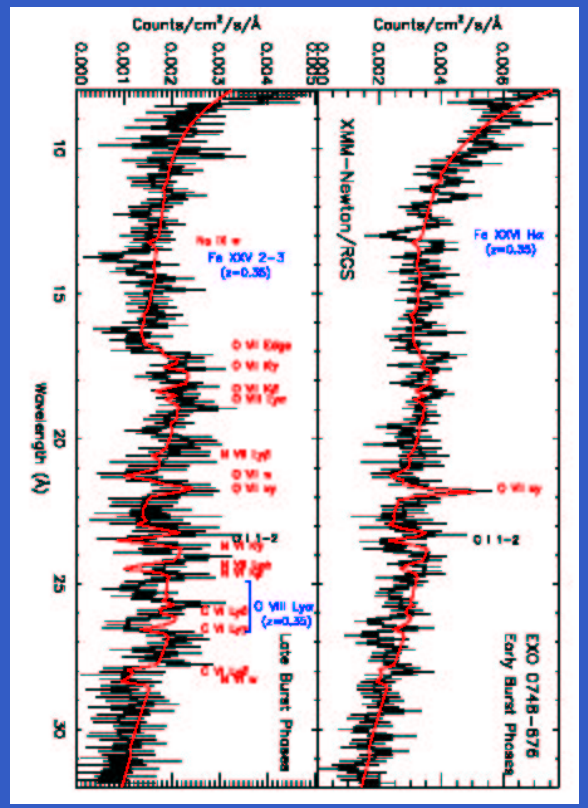
- hot black-body with a size of only $R = 60$ m (from polar caps)
- cool black-body with a size of $R = 10$ km (from hot continent)
- varies with time, not from entire surface!

X-Ray burster

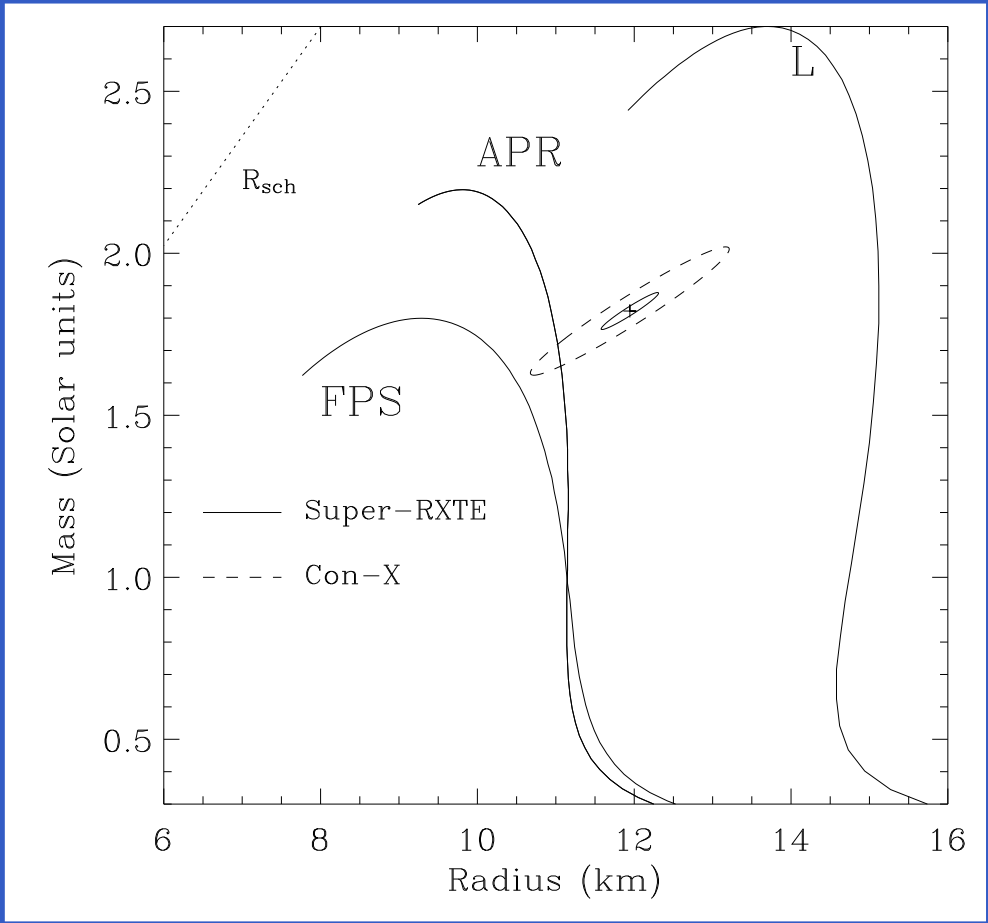




- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- explosion on the surface of the neutron star: x-ray burst
- red shifted spectral lines measured!
  ($z = 0.35 \rightarrow M/M_\odot = 1.5$ (R/10 km))

  (Cottam, Paerels, Mendez (2002))

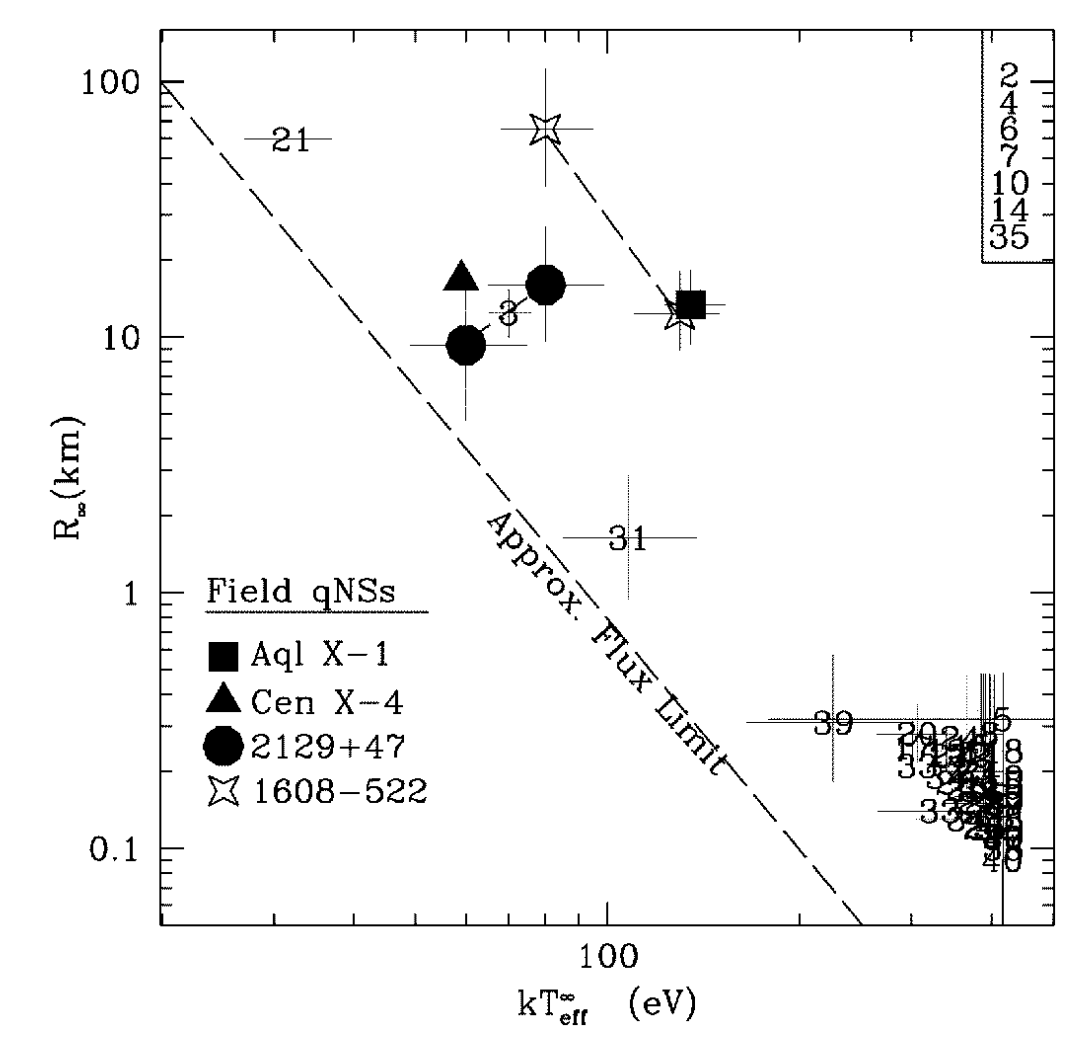
Future Probes Using X–Ray Bursts



(Strohmayer (2004))

- X-ray bursts from accreting neutron stars originating from the surface
- measure profile of emitted spectral lines
- spectral profile is modified from space-time warpage
- $\longrightarrow$ gives a model independent mass and radius!

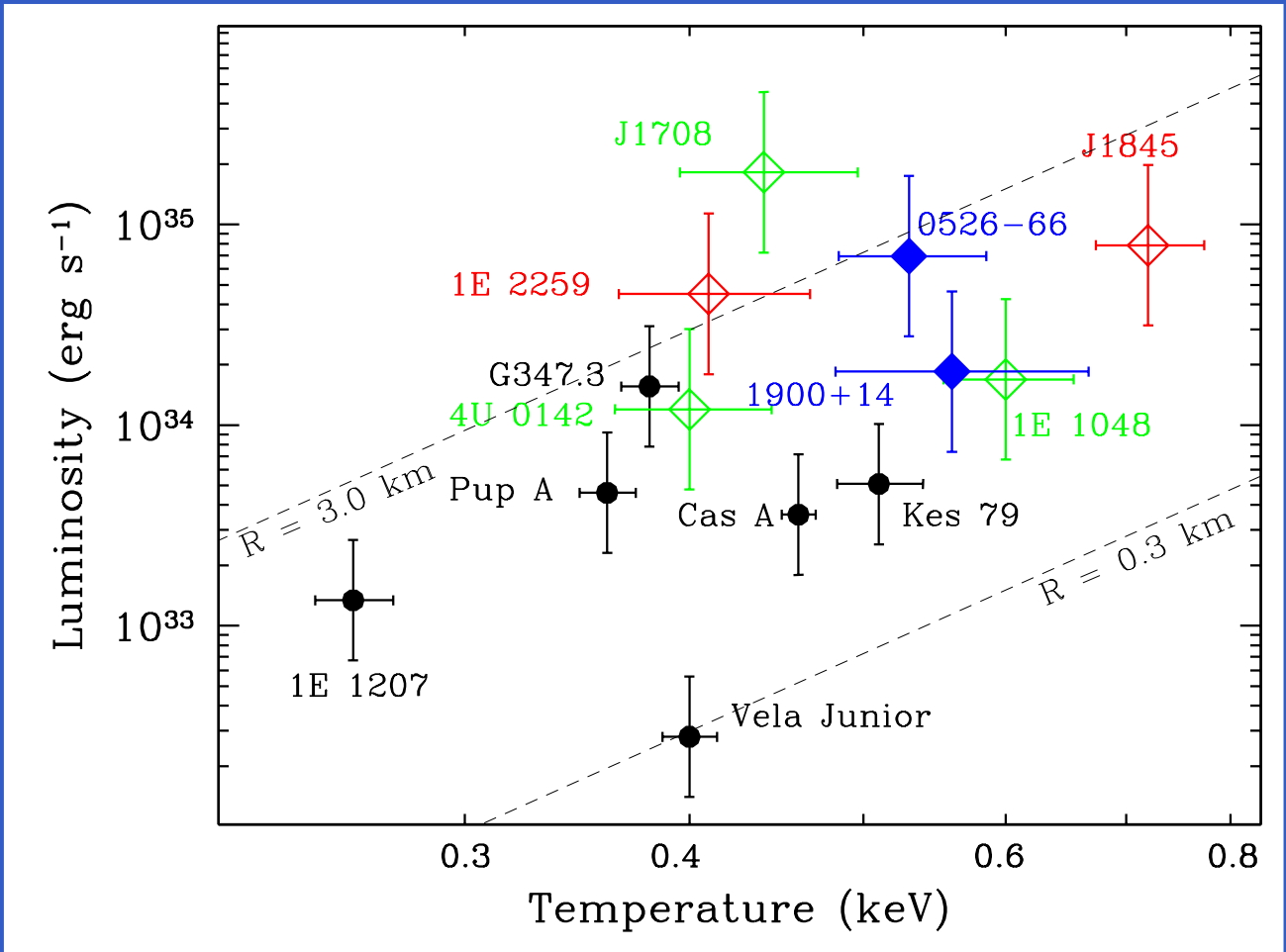
Neutron Stars in Globular Cluster (Rutledge et al. (2002))



- X-ray observations with the Chandra satellite of globular cluster (NGC5139)
- spectra fitted with H atmosphere
- most sources show a hot spot from accretion (extremely small radii)
- quiescent neutron stars found (qNSs): thermal emission from whole surface measurable
- allows to constrain the EoS: $R_\infty = 14.3 \pm 2.5$ km

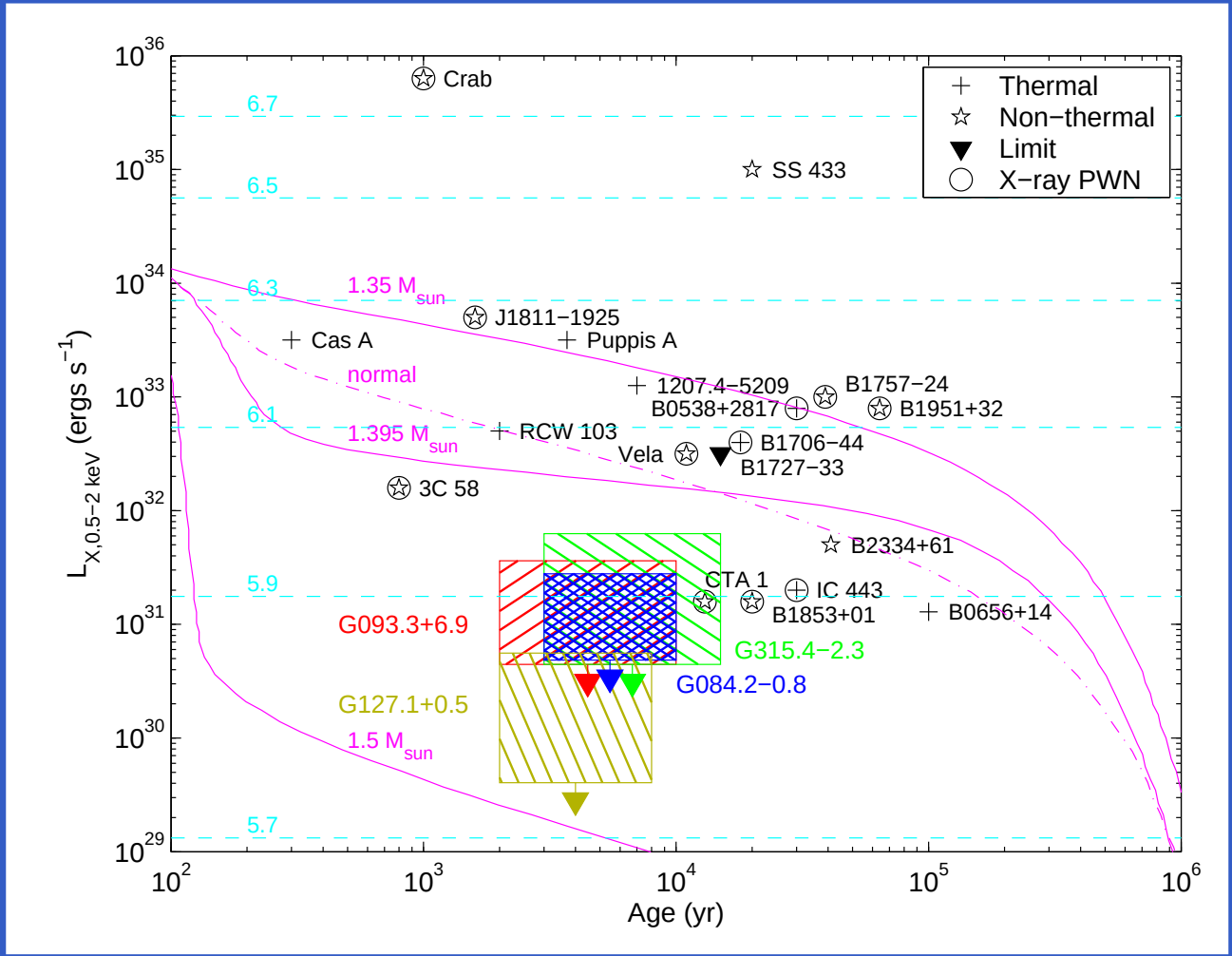
Central Compact Objects (CCOs) in Supernova Remnants

(Pavlov, Sanwal, Teter (2003))



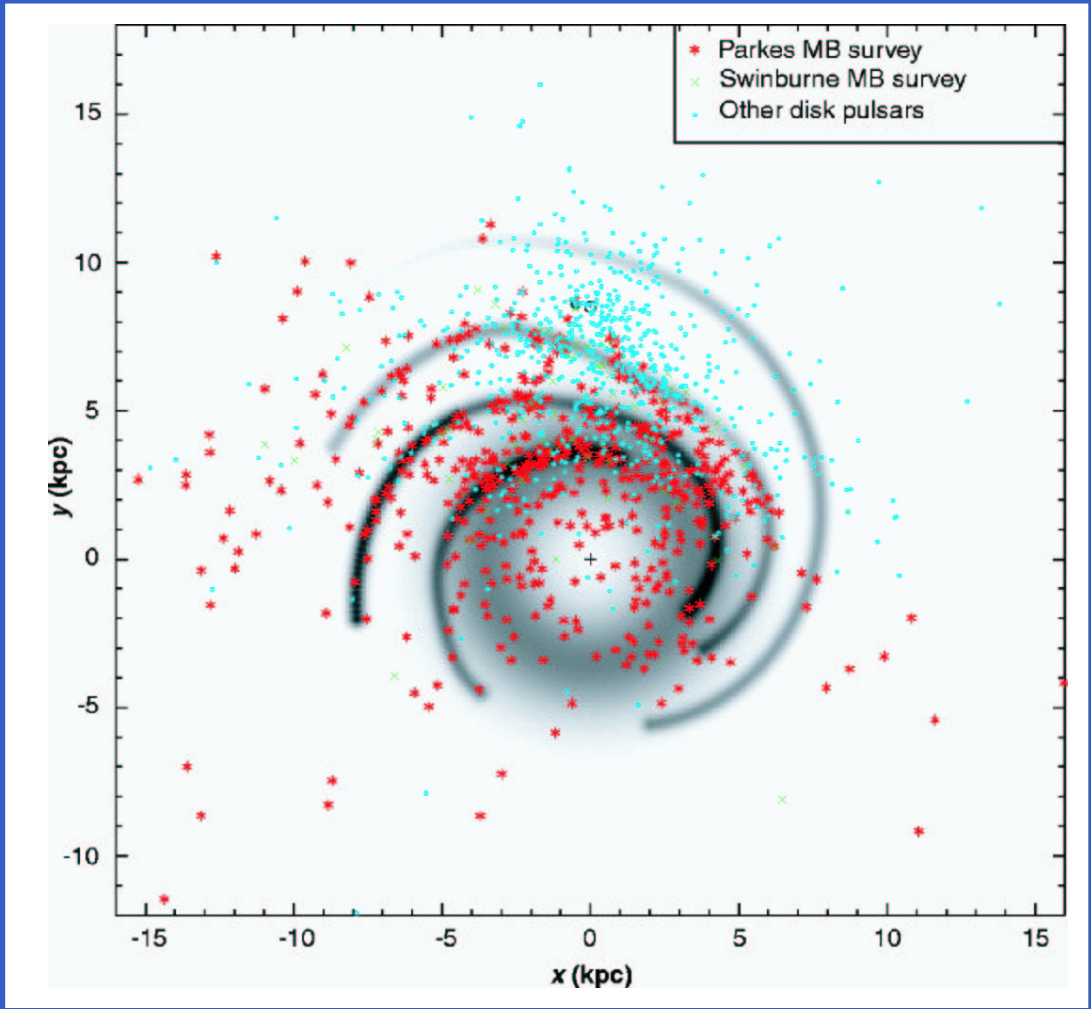
- CCOs: point–like sources in the center of supernova remnants
- only observed in x–rays, radio–quiet, no pulsations seen
- temperatures of 0.2–0.5 keV and sizes of only 0.3–3 km!?!

Cooling of Supernova Remnants (Kaplan et al. (2004))



- known age of the neutron star constrains cooling curves
- newest data from four neutron stars suggest fast cooling
- standard cooling curves are too high!
- signature for exotic matter in the core?

Pulsar Distribution in our Galaxy



- distance estimate by dispersion measure (DM)
- dispersion due to conducting interstellar medium
- works for known electron number density distribution

Future: Square Kilometer Array (SKA)

- receiving surface of 1 million square kilometers
- 1 billion dollar international project
- potential to discover:
  - 10,000 to 20,000 new pulsars
  - more than 1,000 millisecond pulsars
  - at least 100 compact relativistic binaries!
- probing the equation of state at extreme limits!
- cosmic gravitational wave detector by using pulsars as clocks!
- design and location not fixed yet, maybe it will be in South Africa!

movie

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- present data about compact stars is still puzzling and full of surprises
- but the future is bright for peering into the heart of compact stars!

Historical Notes to the Third Family, Quark Stars and Selfbound Stars

- Kurdgelaidze and Ivanenko 1965: collapse to quark stars
- Gerlach 1968: general considerations for a third family
- Kurdgelaidze and Ivanenko 1969: superconducting quark matter
- Heintzmann 1969, Heintzmann and Hillebrandt 1970: Hyperon Stars (ultradense compact stars)
- Libby and Thomas 1969: Mass-Radius plot of ultradense stars
- Itoh 1970: quark star masses ($M/M_\odot \approx 10^{-3}$)
- Heintzmann, Hillebrandt, El Eid, Hilf 1974: Hyperon Stars using Pandharipande's EoS with hyperons
- Hartle, Sawyer, Scalapino 1975: selfbound stars with pion condensation
- Källman 1975, 1976: Abnormal neutron stars (chirally restored matter) and nuggets!

Historical Notes to the Third Family, Quark Stars and Selfbound Stars II

- Brecher and Caporaso 1976: obese quark stars within MIT bag EoS
- Baym and Chin 1976: pure quark star within the MIT bag model (like strange star!)
- Bowers, Gleeson, Pedigo 1977: (unstable) quark stars within scalar-vector field theory
- Fechner and Joss 1978: quark stars besides neutron stars in pQCD!
- Kämpfer 1981, 1983: quark stars and pion-condensed stars as a third stable family
- Haensel, Zdunik, Schaefer; Alcock, Farhi, Olinto, 1986: Strange Stars
- Thorsson et al. 1994: mass-radius plot of a third family for kaon condensed star
- Fujii et al. 1996: kaon-condensed star as a new class of compact stars

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